Interactive Maps for Visually Impaired People: Design, Usability and Spatial Cognition

Anke Brock

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THÈSE

En vue de l'obtention du

DOCTORAT DE L'UNIVERSITÉ DE TOULOUSE

Délivré par :

Université Toulouse 3 Paul Sabatier (UT3 Paul Sabatier)

Présentée et soutenue par :
Anke M. Brock

Le mercredi 27 novembre 2013

Titre :

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Design, Usability and Spatial Cognition

ED MITT : Image, Information, Hypermedia

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Directeur(s) de Thèse :

Delphine Picard - Professor, Aix Marseille University, Institut Universitaire de France
Christophe Jouffrais - CNRS Researcher, IRIT, CNRS & University of Toulouse 3, France

Rapporteurs :

Susanne Boll - Professor, University of Oldenburg, Germany
Vincent Hayward - Professor, Université Pierre et Marie Curie, Paris, France

Autre(s) membre(s) du jury :

Jean-Pierre Jessel - Professor, IRIT, University of Toulouse 3, France
Miguel Nacenta - Lecturer, University of St Andrews, Scotland

to Fabrice

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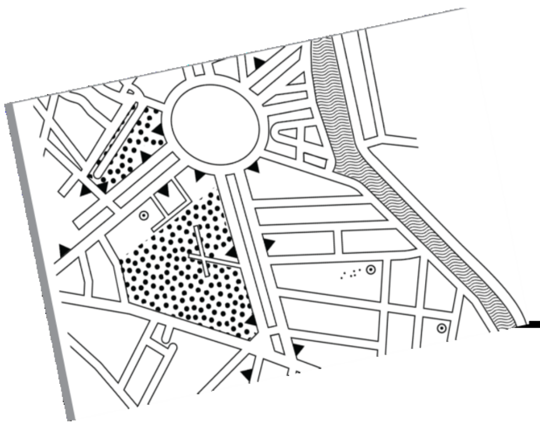


Chapter I

Introduction

I Introduction

I.1 Context

Worldwide, 285 million people are visually impaired (WHO, 2012). This population faces important challenges related to orientation and mobility. Indeed, 56% of visually impaired people in France declared having problems concerning mobility and orientation (C2RP, 2005). These problems often mean that visually impaired people travel less, which influences their personal and professional life and can lead to exclusion from society (Passini & Proulx, 1988). Therefore this issue presents a social challenge as well as an important research area.

Accessible geographic maps are helpful for acquiring knowledge of an urban environment. Traditionally, raised-line paper maps with braille text have been used. These maps have proved to be efficient for the acquisition of spatial knowledge by visually impaired people. Yet, these maps possess significant limitations (Tatham, 1991). For instance, due to the specificities of the tactile sense only a limited amount of information can be represented on the map. Also, specific information such as distances is difficult to represent on raised-line maps. Furthermore, only a small percentage of the visually impaired population can read braille.

Recent technological advances have enabled the design of interactive maps with the aim to overcome these limitations. Indeed, interactive maps have the potential to provide a broad spectrum of the population with spatial knowledge, irrespective of age, impairment, skill level, or other factors (Oviatt, 1997). This thesis aims at providing answers and solutions concerning design and usability of interactive maps for visually impaired people.

I.2 Thesis Statement and Research Questions

The central contribution of this thesis is to demonstrate that interactive maps are an interesting and usable means for providing geographic information to visually impaired people. We suggest the following thesis statement:

Interactive maps are accessible and pertinent tools for presenting spatial knowledge to visually impaired people,
they are more usable than raised-line paper maps
and they can be further enhanced through advanced non-visual interaction.

More precisely we investigated the Research Questions that will be presented in the following subsections and that highlight our main contributions.

I.2.1 Research Question 1

This Research Question was composed by two parts that are closely linked:

- What is the design space of interactive maps for visually impaired people?
- And what is the most suitable design choice for interactive maps for visually impaired people?

We reply to the first part of this question in chapter II. With design space we address the existing solutions for interactive maps for visually impaired people. We performed an exhaustive research of the literature and analyzed the corpus regarding non-visual interaction. We provide an additional analysis of the corpus with regard to terminology, origin of the map projects, timeline and map content and scale in the appendix.

Based on this analysis we investigated the second part of the question in chapter III. More specifically we defined the context as the acquisition of spatial knowledge in a map-like (allocentric) format prior to traveling. We argue in favor of the design of an interactive map based on a multi-touch screen with raised-line overlay and speech output. We present the iterative design process of interactive map prototypes based on this concept.

I.2.2 Research Question 2

- How to involve visually impaired people in a participatory design process?

This question is addressed in chapter III. Participatory design is an iterative design process that includes users from the start to the end of the development. We worked in close collaboration with visually impaired people. However, the methodology of this design process is usually largely based on the use of the visual sense. During this PhD work, we have been facing many situations where the classic participatory methods were not adequate. Consequently, although it was not our central objective, we investigated how the process and design methods could be made accessible. We detail the contribution for each of the four steps of this design cycle: analysis, creation of ideas, prototyping and evaluation.

I.2.3 Research Question 3

- How usable is an interactive map in comparison with a tactile paper map?
- More precisely, how is the resulting effectiveness (spatial knowledge) from exploring an interactive map?

This question is investigated in chapter IV. As mentioned before, there has been no study that compared usability of interactive maps with raised line maps with braille. Thus, so far we do not know whether interactive maps are better or worse solutions than raised-line maps. We reply to this question through an experimental study with 24 blind participants who compared an interactive map prototype with a classical raised-line map. We specifically address usability in the context of acquiring spatial knowledge of an unknown area prior to travelling. Spatial knowledge was part of usability, as effectiveness was measured as spatial cognition scores that resulted from map exploration. We believe that it is interesting to have a separate look on spatial cognition as it is very rich. For instance, it is interesting to study the different types of spatial knowledge (landmark, route and survey), as well as short- and long-term memorization.

I.2.4 Research Question 4

- How can non-visual interaction enhance tactile map exploration?

We address this question in chapter V. More precisely we investigated two sub-questions. First, we propose that the design of usable interaction may benefit from better understanding of how visually impaired people explore tactile maps. Second, we studied the possibility to include further functionality into the map prototype by making use of advanced non-visual interaction. These investigations were only of preliminary nature and open up avenues for future work in this field.

I.3 Methodology

The methodology of this thesis has been divided in several steps (see Figure I.1). First we performed an exhaustive study of the literature on background knowledge, including visual impairment, spatial cognition and (tactile) maps. Furthermore, we proposed a classification of existing interactive maps. Based on this, we have developed interactive map prototypes for visually impaired people following a participatory design process. In this thesis we present how we adapted the process of participatory design to make it more accessible. Based on the proposition by Mackay (2003), we applied a participatory design process in four phases: analysis, generation of ideas, prototyping, and evaluation. The analysis phase allowed us to identify users' needs as well as technical constraints. In the second phase, the generation of ideas, we proposed brainstorming and "Wizard of Oz" techniques for stimulating creativity. In the third phase, prototyping, we developed prototypes through an iterative process. In the fourth phase, evaluation, we compared usability of an interactive map prototype with a classical raised-line map. The outcome of this design cycle has led to preliminary studies on the design of advanced non-visual interaction with the purpose of further enhancing the interactive maps.

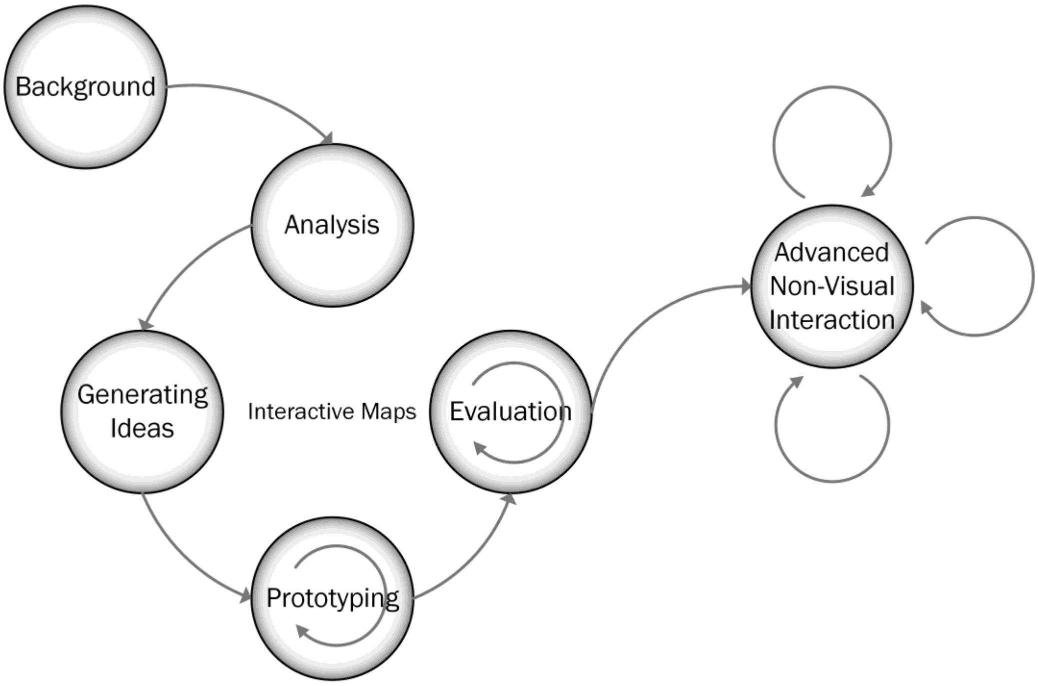


Figure I.1: Methodology of this thesis. The development of interactive map prototypes has been based on a participatory design cycle adapted for visually impaired users. Several micro and macro iterations have been conducted.

I.4 Thesis Walk-Through

The above presented methodology is reflected in the structure of this thesis. This thesis consists of seven chapters (including the present one).

Chapter II details the background of this thesis. As the research field of interactive maps for visually impaired people is multidisciplinary, this chapter includes knowledge from psychology, computer science and human-computer interaction. More precisely we investigate human spatial cognition. We also look at the impact of visual impairment on spatial cognition, as well as the role of the other sensory modalities. Then, we present maps as tools for spatial cognition, and the different types of knowledge related to tactile maps. Furthermore, we study existing interactive map prototypes and specifically non-visual interaction in these prototypes. By doing so we intend to reply to Research Question 1 and open up the design space for accessible interactive maps.

Based on this prior knowledge, chapter III addresses Research Question 1 by justifying and presenting our design choice for interactive map prototypes. Furthermore it also addresses Research Question 2 by demonstrating our adaptation of the participatory design process to include visually impaired people in all design steps (Figure I.1). This chapter also prepares material and methods for the subsequent experimentation.

Chapter IV addresses Research Question 3 as it presents an exhaustive user study with the aim of comparing usability of an interactive map prototype to usability of a classical raised-line map. It also provides a study of the spatial knowledge acquired from exploration of an interactive map.

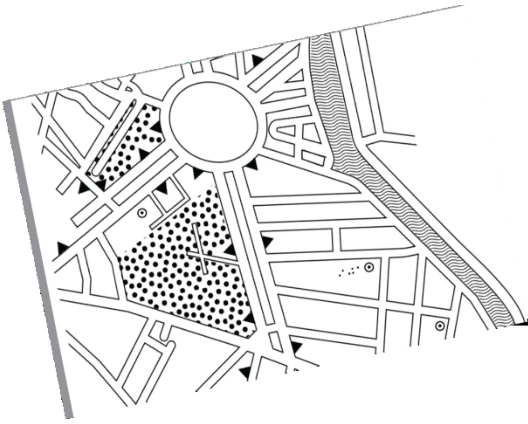
In chapter V we investigate the use of advanced non-visual interaction for further enhancing interactive map prototypes (Research Question 4). In a first step, we propose a tool for better understanding visually impaired people's haptic exploration strategies. In a second step, we explored the use of advanced non-visual interaction for accessing supplementary map information. The preliminary results open up future working perspectives.

Chapter VI summarizes the work presented in this thesis. We describe how each research question was answered and reflect on the thesis statement. The chapter also presents a future work section proposing new avenues for research.

Part of the research work presented in this thesis was presented at peer-reviewed workshops and published in peer-reviewed conferences and journals. The full list of publications is available in Appendix VII.1.

I.5 Reading Hints

- We named the different parts of the thesis as follows: a single number (X) denotes a chapter, two numbers separated by a period (X.X) are called section and all other parts are called subsections.
- In this thesis, all links to websites (such as for companies or products) are listed only at first mention.
- Following the recommendations of the Braille Authority of North America, braille is written with a lowercase.
- This thesis is written in plural, although it represents the work of a single PhD candidate. This is done to acknowledge the contribution of different people without whom this work would not have been possible.



Chapter II

Theoretical Background

II Theoretical Background

The research area of interactive maps for visually impaired people is a multidisciplinary field. It includes psychology through the study of spatial cognition, haptic exploration strategies and the impact of visual impairment on these aspects. It includes computer science, and more precisely human-computer interaction, through the study of interactive map prototypes and non-visual interaction.

This chapter details the theoretical context of our research in these different fields. First, we introduce the context of visual impairment, its definition, distribution and importance for society. We also detail the perception of the different human senses. In a second step, we present spatial cognition and the impact of visual impairment on spatial cognition. Then, we detail maps as a tool for spatial cognition. In this section we present how tactile maps for visually impaired people are designed and produced. We also study how visually impaired people explore and memorize accessible maps. Furthermore we introduce a classification of interactive maps for visually impaired people. More precisely, we investigate terminology, origin of the projects, timeline, map content and user studies of the different projects. We also present a detailed section on non-visual interaction technologies, in which we present multimodal interaction, as well as audio, tactile and gestural interaction techniques that have been used in different accessible map projects. This classification answers to Research Question 1 (What is the design space for interactive maps for visually impaired people?) as it presents various design solutions.

II.1 Visually Impaired People and their Needs

The World Health Organization reports that 285 million people worldwide are visually impaired (WHO, 2012). Improving autonomy and quality of life for this part of the population is therefore a significant challenge for research in assistive technology. In the first section we look more closely at the definition of impairment, disability and handicap. In the second section, we present details on visual impairment.

II.1.1 Impairment, Disability, Handicap

Impairment and disability are not synonyms, even if in daily use they are often employed as such. Cavender, Trewin, and Hanson (2008) define "impairment" as a physical, mental or physiological loss, abnormality or injury that causes a limitation in one or more major life functions. The World Health Organization (WHO) in its "International Classification of Functioning, Disability and Health" (WHO, 2001) defines "activity" as the execution of a task or action by a person and "participation" as involvement in life situations. "Disability" is then defined as a grouping of impairments, activity limitations and participation restrictions. In particular, it concerns the negative interaction of a person's health situation and the environmental and personal factors. The opposite is "functioning" which denotes the positive interaction of a person's health situation and the environmental and personal factors. In other definitions the term "handicap" is used as a synonym of disability (APA - Committee on Disability Issues in Psychology, 1992). It is important to note that every human being can experience a decrement in health or a specific condition which results in some degree of disability (WHO, 2001). For instance a person in a wheelchair and a parent with a stroller experience the same handicap, when trying to access a building surrounded by stairs. Vanderheiden (2012) defines a logical chain: the disability can result in an inability to access standard products, which will then result in a disadvantage as compared to other people that do not experience the same functional limitation. There is a huge variety of impairments. Also a person can have more than one deficiency. In general, the risk of being impaired increases with age (Vanderheiden, 2012).

In many countries, laws were passed to promote the development of accessible information and communication technologies. In France, law no. 2005-102 requires information and communication technology to comply with stringent accessibility standards by 2015 (*LOI n° 2005-102 du 11 février 2005 pour l'égalité des droits et des chances, la participation et la citoyenneté des personnes handicapées, JORF n°36 du 12 février 2005*, 2005). For example, television programs must provide audio description, and electronic and electrical devices must offer accessible solutions. In the United States of America the "Americans with Disabilities Act of 1990" prohibits discrimination due to disability. It also requires American telecommunications companies to provide functionally equivalent services for consumers with impairments.

II.1.2 Visual Impairment

According to the world health organization, 285 million people worldwide are visually impaired (WHO, 2012). Among them, 39 million (around 14%) are blind. In geographical Europe the number of visually impaired people is estimated to over 30 million[2] and 6 million of them are blind. In France, there are approximately 1 492 000 people who have a mild or moderate visual impairment[3]. The number of people with a severe visual impairment is estimated to around 207 000. More precisely, 61 000 of them are blind, which concerns approximately one person out of 1000 in France.

[2] http://www.euroblind.org/resources/information/nr/215 [last accessed August 16th 2013]

[3] http://www.faf.asso.fr/article/la-cecite-en-france [last accessed July 16th 2013]

Most of the impairments could be cured or prevented. This is underlined by the fact that 90% of the people with visual impairment live in developing countries (WHO, 2012). The number of visual impairments caused by infectious diseases has greatly decreased in the past years. On the other hand, as a result of the ageing of the population the number of age-related impairments has increased. In the USA, only 5% of the population under the age of 45 are visually impaired, whereas the number rises to 20% above the age of 75 (Vanderheiden, 2009).

II.1.2.1 Classification of Visual Impairments

The term "visual impairment" comprises a large span of situations ranging from mild vision problems to severe impairment; such as light perception only or complete loss of vision. Mild and severe visual impairment include a variety of vision problems such as myopia, far-sightedness, astigmatism, color blindness, night blindness, extreme sensitivity to light, dimness, haziness, foggy vision, spots in the visual field or reduced visual field.

Table II.1: Classification of Visual Impairment based on visual acuity as defined by (WHO, 2010).

Category Nr	Category Title	Visual acuity worse than	Visual acuity equal or better than
0	Mild or no visual impairment		6/18, 3/10, 20/70
1	Moderate visual impairment	6/18, 3/10, 20/70	6/60, 1/10, 20/200
2	Severe visual impairment	6/60, 1/10, 20/200	3/60, 1/20, 20/400
3	Blindness	3/60, 1/20, 20/400	1/60, 1/50, 5/300
4	Blindness	1/60, 1/50, 5/300	Light perception
5	Blindness	No light perception	
9		Undetermined	

The World Health Organization (WHO, 2010) proposes a classification in several categories based on visual acuity (see Table II.1). Visual acuity is calculated as the quotient of the distance from which a specific person sees an object and the distance at which the same object is seen by a person without visual impairment. For example, an acuity of 6/60 means that the object perceived at 60 meters distance by a person with normal vision must be at 6 meters distance from the visually impaired person to be perceived in the same way. Additionally the visual field can be taken into account. The visual field is the total area in which an object can be detected while the eye is focused on a central point. The normal field spreads 60 degrees nasally, 100 degrees outwards, 60 degrees above and 75 degrees below the horizontal meridian (Cattaneo & Vecchi, 2011). A person is also defined as blind (category 3, see Table II.1) when the visual field is no greater than 10° around the central fixation point (even if acuity may be better than level 3). Furthermore, the WHO differentiates between binocular and monocular visual impairment. In the United States, the term "legal blindness" is defined as having a visual acuity of 20/200 or less, or having a visual field of 20 degrees or less (Lévesque, 2005). It is therefore possible that people who are referred to as blind still have light perception, i.e. they can differentiate between a bright and a dark environment.

II.1.2.2 Other Influential Factors

Besides the nature and degree of visual impairment, another important aspect is the age at onset of the impairment. In many studies blind participants are classified into "early blind" and "late blind". Thinus-Blanc and Gaunet (1997) observed that this classification was not coherent in all studies. Sometimes "early blind" refers to "before the age of three"; sometimes it refers to "before the age of one". Lebaz, Picard, and Jouffrais (2010) proposed the proportion of life-time without visual experience as a more precise view of inter-individual differences. Proportion of life-time without visual experience is calculated as the ratio between the life-time spent with blindness and the current age. As an example; a ratio of 0.10 indicates that the person has spent 10% of his/her life without visual experience. Lebaz et al. observed a significant relation between strategies for exploring tactile images and proportion of life-time without visual experience. Strategy is hereby defined as a set of functional rules used by the participant for information processing, from the first encounter with a new situation until the externalization of the spatial knowledge (Thinus-Blanc & Gaunet, 1997). In any case, multiple studies have proved an influence of the age at onset of blindness on cognition (Ungar, 2000). For instance, congenital blindness might lead to a delayed development of sensorimotor coordination which then again may negatively impact spatial cognition (Thinus-Blanc & Gaunet, 1997).

Another influential factor is the cause of the impairment which can be genetic, related to an illness or accidental. The cause again can have an impact on the affective reaction to the impairment. If the impairment appears suddenly, it is likely to lead to depression (Thinus-Blanc & Gaunet, 1997). Congenital blindness will also more likely lead to autism or stereotyped behaviors. In the appendix (VII.2) we present a glossary of different eye diseases.

II.1.2.3 Consequences of Visual Impairment and Assistive Technology

Visual impairment may result in a reduction of autonomy in daily life. Very often information is presented in visual form only and visually impaired people are thus excluded from accessing this information. This concerns important domains such as administrative tasks and education. Challenges are also related to mobility and orientation (see Figure II.1). In a report on visually impaired people in France, 56% of them declared having problems concerning mobility and orientation (C2RP, 2005). These problems often mean that visually impaired people travel less, which influences their personal and professional life and can lead to exclusion from society (Passini & Proulx, 1988). Therefore this issue presents a social challenge as well as an important research area.

Figure II.1: Challenges for a visually impaired traveler in daily life. Displays of grocery stores and road works are blocking the way. Reprinted from (Brock, 2010a).

The aim of Assistive Technologies is to overcome these limitations. Vanderheiden (2012) presented a list of assistive technologies for blind people. This list includes modalities such as braille, tactile symbols, raised-line drawings or synthetic speech. It also includes devices that are based on these modalities, such as braille displays, talking clocks and calculators, screen readers or audio description for television. The list also presents technology that is helpful to memorize information such as speech recorders or braille-based portable note takers. Finally mobility aids include white canes, navigation systems or talking signs. However, these technologies are not accessible to everyone as cost may be important. Also, it can be challenging to learn how to use the technology (C2RP, 2005).

II.1.3 Qualities and Differences of Human Sensory Systems

In order to understand the challenges that a visually impaired person faces, it is important to understand the qualities of our senses and the differences that exist between them. Vision is the sense that sighted people will normally rely on the most, even if the other senses can provide useful information (Thinus-Blanc & Gaunet, 1997). Vision provides a large amount of information (Cattaneo & Vecchi, 2011). It is indeed the most efficient sense for gathering environmental information (Jacobson, 1998a). Yet, for some tasks, vision is not the most adapted sense. An example is sitting in a stationary train while an adjacent train starts to move off. Our visual sense tricks us into feeling that our train is moving. Kinesthetic information will tell us that we are static (Ungar, 2000). Most activities are based on the simultaneous and interactive participation of different senses. Exchanges between people and their environment are multimodal and must be integrated through complex processes (Hatwell, 2003).

To better understand this, we will have a separate look at the three senses that are most commonly employed in interactive systems: vision, audition and touch. As the senses of smelling and taste are so far very rarely employed in assistive technology, we will exclude them from this presentation.

II.1.3.1 Vision

The sensors for the sense of vision are the eyes. Vision works without direct contact. Vision allows the simultaneous viewing of a large spatial field. The point of foveation itself is quite limited, yet other objects are still present in peripheral vision. It is possible to perceive nearby and far objects (Ungar, 2000). Vision is the only sense that allows this simultaneous perception and thus gives a global view of an environment. Each eye perceives a two-dimensional image. It is possible to recreate a 3D image and thus gain information on distances and depth by integrating information on vergence and disparity from both eyes, but also on occlusion, shades, light, gradients of color, texture, size and information (Hinton, 1993).

Vision excels in different fields. Among them are perception of space, landmarks, directions, distances, orientation and speed of moving objects. Vision has the greatest spatial resolution of all senses and is best adapted for coordinating movements in space (Cattaneo & Vecchi, 2011) and for avoiding obstacles (Hatwell, 2003). Finally, it is also well adapted for recognizing shape and material of objects (Thinus-Blanc & Gaunet, 1997).

On the downside, vision has poor alerting functions as compared to other senses (Cattaneo & Vecchi, 2011). Despite its strength in many areas, vision can be tricked. In addition to the moving train illusion cited above, other illusions that concern the perception of size, color or symmetry are well known. Equivalence between visual and haptic illusions has been demonstrated (Gentaz, Baud-Bovy, & Luyat, 2008).

II.1.3.1 Audition

The sensors for audition are the ears. Sound is transmitted as a wave. Its frequency—measured in Hertz—determines the pitch; its intensity—measured in dB—determines the loudness (Cattaneo & Vecchi, 2011). As for vision, no direct contact is necessary. In comparison with vision, it is more difficult to perceive several sources at a time. Audition is better at treating information successively, in a distinct order which is important for speech as well as music (Hatwell, 2003).

Audition is best adapted for the perception of temporal stimuli such as length, rhythm and speech (Hatwell, 2003). Indeed speech is a powerful means of communication that has similar properties as written text (Blattner, Sumikawa, & Greenberg, 1989). Audition is also well adapted for perceiving distances, as the perceived loudness decreases with increasing distance. The sound source can be localized using the three values azimuth, elevation and range (Cattaneo & Vecchi, 2011). The movement of objects can be recognized through Doppler effects, i.e. changes of frequency (Nasir & Roberts, 2007). Furthermore, objects can be identified based on the specific sound they emit (Gaunet & Briffault, 2005). Finally, audition has good alerting functions as we automatically react to unexpected sound (Cattaneo & Vecchi, 2011).

On the negative side, audition is a vulnerable sense. Even if it is possible to filter out meaningful information from noise, audio signals are subject to interference, especially in urban areas. Additionally, it is not possible to recognize precise object properties such as shape, size, color, texture or material (Gaunet & Briffault, 2005). Also, spatial acuity is quite poor. As for other senses, illusions exist. Reflections can trick the perception of direction. If the temporal delay between the original sound and the reflection is big, we perceive it as echo (Cattaneo & Vecchi, 2011). Finally, it is possible that sound cues are missing as every object has visible features but not every object emits sound (Thinus-Blanc & Gaunet, 1997).

II.1.3.2 Somatosensory System (Touch)

Touch or tactile perception is sometimes referred to as “somesthetic senses” or "somatic senses". The latter names make clear that touch comprises different types of perception. Concretely, we will explain three types of tactile perception: cutaneous, kinesthetic and haptic perception.

Cutaneous perception concerns the touching of the skin of any part of the body which remains motionless. This is perceived by mechanoreceptors and thermoreceptors in the skin (Lederman & Klatzky, 2009). Perceptual processing only concerns information related to the stimuli applied to the skin without exploratory movements. The sensors for touch are spread over the whole body (Hatwell, 2003). The accuracy of the detection of the tactile stimulus is higher with greater density of receptors and a reduced size of the receptive field (Cattaneo & Vecchi, 2011). For this reason, the accuracy of tactile perception in the fingertips is superior to other body parts.

Kinesthetic perception is based on the deformation of mechanoreceptors in muscles, tendons and joints, such as in the arm-shoulder system (Gentaz, 2003). The kinesthetic sense perceives the relative position and movement of body parts. Muscle receptors provide information on the length of muscles and speed of change; tendon receptors provide information on the level of tension in the muscle; the role of joint receptors is still debated but might refer to angle perception and/or facilitation of proprioception. Kinesthetic perception may also come from the integration of the motor command that is addressed to the muscles.

Haptic perception involves the combination of cutaneous and kinesthetic perceptions in a complex manner across space and time (Gentaz, 2003). It is a dynamic process that combines the cutaneous perception with movement, for instance when exploring a three-dimensional object. Cutaneous perception is referred to as "passive" and haptic perception as "active" (Golledge, Rice, & Jacobson, 2005). While being passively touched, people tend to focus their attention on their own bodily sensations. While actively exploring, people tend to focus on properties of the external environment (Lederman & Klatzky, 2009).

During tactile perception, direct contact with the perceived environment needs to be established and perception is limited to the contact zone (Hatwell, 2003). However objects, such as a white cane, can be used as an extension of the own body (Gaunet & Briffault, 2005). Touch perception differs from vision in that there is no peripheral perception. Besides, in contrast to vision, touch perception is sequential, i.e. we need to explore an object part by part. In contrast to audition, touch is segmented and the order of perception is not fixed, i.e. we can decide in which order we explore an object but not in what order we listen to the notes of a musical piece. Skin sensations cease as soon as the physical contact ends. The objects not currently examined must be maintained in memory and no cues are available to draw attention in any particular direction (Ungar, 2000). This implies a high charge for working memory as the person needs to make a mental effort to integrate a unified representation of an object or environment (Hatwell, 2003). Therefore Hinton (1993) argues that every tactile perception has two components, a sensory and a memory component.

Lederman and Klatzky (2009) differentiate "what" and "where" systems. The "What" system deals with perceptual (and memory) functions. It serves the recognition of objects and is especially used for identification of physical and geometrical properties. Touch excels in the perception of physical properties of objects, such as shape, texture (roughness, stickiness, slipperiness or friction), size (measured for instance as total area, volume, perimeter), compliance (i.e. deformability under force), temperature or weight

(Hatwell, 2003). Familiar objects are thus recognized very quickly. Different exploratory movements are applied for exploring different characteristic (Lederman & Klatzky, 2009). For instance, texture is explored via a lateral movement, hardness via a pressure movement, and global shape via contour following. Picard et al. (2003) demonstrated that participants were able to associate tactile descriptors with different fabrics experienced by touch. The "Where" system, on the other hand, provides a description of the spatial relation of objects in the world. It can identify direction, localization and distances. Localization can be done with respect to either an egocentric reference frame (distances and directions are specified relative to one's own body), or to an allocentric (i.e., external) reference frame. Evidence for a "what/where" distinction for the somatosensory system is derived from fMRI as well as behavioral studies (Lederman & Klatzky, 2009). Furthermore human tactile perception is considered to have high temporal acuity. Humans are capable of distinguishing successive pulses with a time gap as small as 5 ms, whereas it is 25 ms for vision (Choi & Kuchenbecker, 2013). Only audition is more precise with 0.01 ms.

On the downside, spatial discrimination with the finger is less accurate than with the eye. Different tests exist for measuring thresholds of tactile spatial acuity (Lederman & Klatzky, 2009). The results vary between 1 and 4 mm for the fingertip. Tactile spatial acuity varies significantly across the body surface, with the highest acuity on the fingertips and lowest on the back. Moreover, as for the visual sense there are also illusions for the sense of touch. In the radial-tangential illusion, radial lines (lines going towards the body or from the body outwards) are overestimated compared to tangential lines (side to side) of the same length. In addition, according to Gentaz et al. (2008) it is more difficult for humans to understand the characteristics of an oblique line as compared to a horizontal or vertical line. They argued that people use a vertical and horizontal frame of reference. Encoding oblique lines requires thus more calculation. Besides, curved lines are perceived as shorter than straight lines (Cattaneo & Vecchi, 2011). Finally, systematic distortions are possible because parts of the body are moving (e.g. the position of the hand in relation to the body), and because a force is exerted to pursue an exploration task (Golledge et al., 2005).

II.1.4 Specificities of Blind People

The interest for understanding specificities of blind people is based on Molyneux's problem. In 1688, Irish philosopher William Molyneux sent a letter to John Locke in which he asked whether a person who has been born blind and who has learnt to distinguish a sphere and a cube by touch, would be able to distinguish these objects by vision, once he had regained sight. Only recently Held et al. (2011) provided an answer to this question. Their study showed that congenitally blind people who gained sight after eye surgery did not immediately succeed in visually recognizing shapes that they had explored by touch before. However this ability was acquired after a very short time which suggests a coupling between the representations of both modalities based on experience. As argued by Cattaneo and Vecchi (2011), vision does not only require functional eyes and optical nerves, but also functioning brain structures in order to create mental representations. It has originally been assumed that visually impaired people were incapable of creating mental representations (deficiency theory, see Fletcher, 1980). Today, it is known that mental representations can be created without sight but that these representations differ from those developed by sighted individuals (difference or inefficiency theory).

It is interesting to take a closer look at the differences for each of the senses. Concerning audition, studies have revealed both advantages and disadvantages for blind people and sometimes results are contradictory. However, there is a general tendency that especially congenitally blind people outperform sighted people on different auditory tasks (Cattaneo & Vecchi, 2011). This advantage could even be confirmed in studies when the prior musical experience of sighted and visually impaired participants was controlled. Blind people could perceive ultra-fast synthetic speech and pseudo speech that is impossible to understand for sighted people. They also showed an improved memory for auditory and verbal information as well as an improved serial memory. This improvement of memory appears to depend on an improved stimulus processing and encoding. Concerning the localization of auditory cues, two theories exist (Cattaneo & Vecchi, 2011). The deficit theory argues that visual calibration is needed for auditory localization to work properly. The compensation theory argues that multimodal mechanisms compensate for the vision loss. Results of different studies are controversial and depend on the presentation of the stimulus and on the method of pointing to the stimulus (Thinus-Blanc & Gaunet, 1997). For instance, Macé, Dramas, and Jouffrais (2012) observed that performance of blind users did not differ in accuracy from sighted users' performance in an auditory object localization task. Cattaneo and Vecchi (2011) argue that localization of auditory cues is possible without vision even if it may be impoverished. They propose that blind people are able to calibrate localization through their own body movements like turning the head or moving towards another position. Finally, early blind people can develop echolocation, which demands a subtle processing of sound (Thinus-Blanc & Gaunet, 1997). Echolocation is based on sounds created by the listener, for instance clicking noises with the tongue, which are reflected from objects (Stockman, 2010). This phenomenon can even serve as an additional sense of orientation.

Tactile capacities can be evaluated with haptic test batteries (see for instance Mazella, Picard, & Albaret, 2013). Findings of different studies on tactile capacities are again not consistent and depend on inter-subject variability and task type. It is also important to say that different results may be observed depending on how important a test task is in the daily life of a visually impaired person. Moreover, congenital blind participants have revealed to be superior to sighted people in temporal-order judgments (Cattaneo & Vecchi, 2011). It appears that tactile acuity is retained with age in blind people, but not in sighted people. Also studies revealed superior tactile acuity for blind people, independently of braille reading skills, previous visual experience or remaining light perception. However, sighted people were able to gain tactile acuity after training (Cattaneo & Vecchi, 2011). The precise relation between visual deprivation, training and tactile acuity, still needs further investigation.

II.2 Visual Impairment and Spatial Cognition

When studying interactive maps, it is first important to understand how human beings perceive and process map information. In the following subsections we review spatial cognition as the basis of this process. In a second step, we will look at the specificities for visually impaired people.

II.2.1 Spatial Cognition

Spatial cognition concerns not only human beings, but also non-primates (Tolman, 1948), and can even be applied to robots (Kuipers & Levitt, 1988). In this thesis we focus on spatial cognition in humans.

II.2.1.1 Defining Spatial Cognition

Montello (2001) defines spatial cognition as the study of knowledge and beliefs about spatial properties of objects and events in the world. “Cognitive map” is another important term. It has been coined by Tolman (1948) who investigated spatial cognition in rats. It has further been based on the work on city planning by Kevin Lynch (1960) who stated that people’s behavior and experience depended on the images that they create about these cities. Synonyms for “cognitive map” include imaginary map, mental map, environmental image, spatial image, spatial schema, and spatial representation (Siegel & White, 1975). Downs and Stea (1973) defined cognitive maps as comprehensive representations of the environment created from aggregated information. Cognitive maps contain knowledge about landmarks, route connections, distance and directions, but can also include non-spatial attributes and emotional associations (Montello, 2001). Cognitive mapping is the process composed by psychological transformations by which an individual acquires, codes, stores, recalls and decodes information about the relative locations and attributes of phenomena in his everyday spatial environment (Downs & Stea, 1973). Research suggests that cognitive maps are not organized like a cartographic map in the head (Downs & Stea, 1973; Montello, 2001; Siegel & White, 1975). Cognitive maps are not unitary integrated representations. They are often fragmented, augmented, schematized, or distorted. Sometimes they are composed by several separate pieces that are interlaced, linked or hierarchically related (e.g., France as a smaller entity is part of Europe as a larger entity). Cognitive maps are part of our daily lives as they are the basis for all spatial behavior (Downs & Stea, 1973). Primary functions of spatial representations are facilitation of location and movement in (large-scale) environments, prevention from getting lost, finding one's way and providing frames of reference for understanding spatial information (Siegel & White, 1975). The process of transformation of information from absolute space to relative space demands operations such as change in scale, rotation of perspectives, abstraction, and symbolization. The necessary information to create such a cognitive map is location information (where is the object) and attributive information (what kind of object) (Downs & Stea, 1973). Spatial properties of objects include size, distance, direction, separation and connection, shape, pattern, and movement (Montello, 2001).

Spatial knowledge is acquired, stored, retrieved, manipulated and used (Montello, 2001). Different mechanisms used for treating this knowledge include sensation and perception, thinking, imagery, memory, learning, language, reasoning and problem-solving mechanisms. Spatial knowledge is acquired through our sensorimotor system through direct experience of the environment (Montello, 2001). In most cases it is a result of inter-sensory connections (for sighted people primarily visual-motor-kinesthetic) and not of a single sense (Siegel & White, 1975). Alternatively, people acquire spatial knowledge indirectly via symbolic media such as maps and images, 3-D models, and verbal descriptions (Gaunet & Briffault, 2005; Jacobson, 1996; Picard & Pry, 2009). We will detail maps as a tool for acquiring spatial knowledge in subsection II.2.2.5.

Spatial knowledge is dynamic. It changes over time through processes of learning and development (Montello, 2001). "Recognition-in-context-memory" is an early learning mechanism. It associates information with landmarks, such as when it occurred or what it is connected to (Siegel & White, 1975). Knowledge of the location of objects becomes more accurate with increased experience (Thorndyke & Hayes-Roth, 1982). Downs and Stea (1973) propose three extents to which experience of a spatial environment can affect existing spatial knowledge. First, it can have no effect and just confirm prior knowledge. Second, locations and attributes can be added. Finally, it can lead to a complete reorganization. However, cognitive maps are relatively resistant to change and it requires an accumulation of contrary evidence before complete reorganization happens. After a delay of time, precision of spatial representation declines and information is forgotten (Downs & Stea, 1973; Giudice, Klatzky, Bennett, & Loomis, 2013).Worse loss of spatial knowledge or spatial skills can result from brain damage (Siegel & White, 1975).

Further definitions concern the distinction between orientation, wayfinding, locomotion and navigation. Montello (2001) defines orientation as "knowing where you are". Orientation is composed by two processes: recognition of external features and dead reckoning, also called path integration or inertial navigation. The latter is the update of a sense of orientation by integrating information about movement, speed, direction and acceleration from the vestibular and proprioceptive systems (Cattaneo & Vecchi, 2011). Furthermore, Montello defines locomotion as guiding oneself through an environment in response to sensorimotor information in the immediate surroundings. Identifying surfaces (e.g., tactile paving), avoiding obstacles and advancing towards landmarks in the immediate environment are part of locomotion. This does not demand the prior acquisition of a cognitive map. Wayfinding refers to a person's ability to reach destinations outside the immediate sensory field. It includes the planning and decision-making needed for reaching a destination (Passini & Proulx, 1988). Choosing routes, orientating to nonlocal features, and interpreting verbal route directions are part of the wayfinding process (Montello, 2001). These tasks are impossible without having developed a cognitive map. Finally, navigation is defined as the combination of locomotion, wayfinding and orientation. It involves position updating with respect to the planned routes, and reorienting travel toward the destination in the event of becoming lost (Loomis, Golledge, & Klatzky, 1998). Navigation is based on the prior acquisition of a cognitive map or can be assisted by navigational aids such as maps or navigation systems (Ishikawaa, Fujiwarab, Imaic, & Okabec, 2008). Navigation, wayfinding, locomotion and orientation are dynamic processes (Cattaneo & Vecchi, 2011). In this thesis, the focus is on acquiring spatial knowledge from maps and thus locomotion and navigation will not be further investigated.

II.2.1.2 Different Types (Landmark, Route and Survey) and Frames of Reference for Spatial Knowledge

Siegel and White (1975) differentiate three types of spatial knowledge: landmark, route and survey. They define landmarks as specific geographic locations, strategic places to which a person travels. Landmark knowledge is considered information about distinctive environmental features in their spatial and temporal context (Magliano, Cohen, Allen, & Rodrigue, 1995). During travel, landmarks are used as proximate coursemaintaining devices. It has been shown that they play an important role also for map reading (Roger, Bonnardel, & Le Bigot, 2011). Landmark knowledge is predominantly of visual nature for human adults (Siegel & White, 1975). Second, routes are defined as an ordered sequence of landmarks and represent familiar lines of travel. There are many possibilities to connect landmarks. Route selection typically accommodates time constraints, overall distance covered, and ease of access (Magliano et al., 1995). People must at least identify locations at which they must change direction and take action. Optionally, they possess knowledge about distances, angles of turn, terrain features or memories of traversed routes (Thorndyke & Hayes-Roth, 1982). This knowledge type is predominantly of sensorimotor nature (Siegel & White, 1975). Finally, survey knowledge (also called configurational knowledge) is a multidimensional representation of spatial relations involving a set of distinctive environmental features (Magliano et al., 1995). It is comparable to a map based on gestalt elements. It includes topographic properties of an environment; location and distance of landmarks relative to each other or to a fixed coordinate system (Thorndyke & Hayes-Roth, 1982). Survey knowledge is considered more flexible than route knowledge. When based on route knowledge, travelers are restricted to the routes they have previously memorized. On the contrary, survey knowledge provides a global representation of an area and allows flexible travel (Jacobson, 1996). The type of exposure to spatial knowledge influences what type of knowledge a person acquires. Thorndyke and Hayes-Roth observed that route knowledge was normally derived from direct navigation, whereas map exploration led to the acquisition of survey knowledge. Although it is possible to acquire survey knowledge from direct experience, it can be obtained more quickly and with less effort from map reading. Magliano et al. observed that subjects remembered different types of map knowledge (route or survey knowledge) depending on the instruction given before exploration of space. They also observed that landmark knowledge was always obtained first as a basis for the two other knowledge types.

Another distinction is to be made between allocentric and egocentric reference frames. Allocentric is defined as relative to some external framework (e.g., cardinal directions, or with regard to an external point of interest); egocentric is defined as relative to one's own body and movement (Ungar, 2000). Allocentric knowledge is perceived from a "bird's eye view", whereas egocentric knowledge is perceived from the observer's perspective. Egocentric in contrast to allocentric representations are characterized by serial aspects rather than spatial ones (Thinus-Blanc & Gaunet, 1997). Route knowledge is represented in an egocentric reference frame, whereas survey knowledge is represented in an allocentric reference frame. Accordingly, allocentric representations are more flexible than egocentric representations, as the person can come up with alternative routes. Egocentric representations are updated as the person moves in space, whereas allocentric representations are not (Cattaneo & Vecchi, 2011). Both representations coexist in parallel and are combined to support spatial behavior.

II.2.1.3 Storing Spatial Information

Spatial memory is composed by a short-term (working memory) and a long-term spatial memory (Giudice et al., 2013). Spatial working memory allows actively imagining layouts, performing mental rotations of these layouts and navigating without immediate perceptual support. Long-term spatial memory enables travel planning (wayfinding) and recognition of known landmarks. Different spatial tests have shown that representations in short-term memory correspond to an egocentric perspective, whereas representations in long-term memory correspond to an allocentric perspective (Cattaneo & Vecchi, 2011). Short-term input can be perceptual input (from vision, audition and touch), from language and from existing knowledge in long-term memory. Loomis, Klatzky, and Giudice (2013) introduced the term "spatial image" as an active working-memory representation of locations in the three-dimensional environment. There is an ongoing debate on how input from different sources is stored in short-term spatial memory (Picard & Monnier, 2009). The three main possibilities are 1) separate and modality-specific storage; 2) storage in a common system in an abstract format regardless of nature of input modality; 3) conversion of input either in verbal or visuo-spatial format. Picard and Monnier observed a parallel learning curve for tactual-spatial and visual-spatial memory span across ages. This suggests that common cognitive mechanisms exist for both modalities. Also, they observed functional equivalence between tactile and visual sense for learning spatial arrangements, when the visual sense is restricted to serial input (as is the case for the tactile sense). These finding argue against the theory of separate storage for input from different modalities. Similarly, Loomis et al (2013) observed functional equivalence of the senses in different experiments. Besides, Giudice et al. (2013) reported that these different sources led to composite representations that were insensitive to the origins of the knowledge. To sum up, these studies suggest that spatial input from different modalities is stored in a common short-term memory.

II.2.1.4 Inter-Individual Differences

Studies on spatial cognition are sometimes contradictory. Often, this can be explained by inter-individual differences that impact spatial cognition. Montello (2001) distinguishes between "ability differences" and "stylistic differences". The latter describes different but effective strategies, whereas the former describes a difference of knowledge or skills. He outlines determining factors such as age, gender, body size, education, expertise, social status, language and culture.

Studies on gender-related differences are controversial (Linn & Peterson, 1985), but most studies confirm an advantage for male as regard to female persons. For instance Coluccia, Iosue, and Brandimonte (2007) observed that male participants were faster in learning a map, more accurate in map drawing, and showed higher levels of performance on road drawing than female participants. The most prominent explanations for these differences are biological factors—hormones or genes—or socio-cultural factors—spatial experience depending on socialized roles (Bosco, Longoni, & Vecchi, 2004). Coluccia et al. observed that map learning strategies differed between male and female participants. Disadvantages for women occur not in all spatial tasks, but mostly in those related to mental rotations (Linn & Peterson, 1985). For instance, Bosco et al. observed an advantage for men over women in tasks based on visuo-spatial working memory but no significant difference in orientation tasks.

Many studies have observed differences of spatial cognition between sighted and visually impaired people. We will investigate this difference in detail in the following subsection.

II.2.2 Spatial Cognition without Sight

Spatial cognition of sighted people is largely based on the visual sense (Cattaneo & Vecchi, 2011). Vision allows the perception of a large spatial field. Peripheral objects are detected without actively focusing on them. Vision also provides a spatial reference frame. From early childhood, vision contributes to the learning of spatial skills. This raises the question whether spatial cognition without sight is possible and what differences exist between sighted and visually impaired people.

II.2.2.1 Spatial Cognition and Specificities for Visually Impaired People: deficient, inefficient or different?

Three different and controversial theories describe the impact of visual impairment on spatial cognition: deficiency theory, inefficiency theory and difference theory (Fletcher, 1980). The deficiency theory was the first one to be introduced. It argues that the lack of visual experience results in a total lack of spatial understanding. Inefficiency theory in contrast says that the lack of visual experience results in spatial abilities which are similar but necessarily less efficient than those of sighted people. Finally, the difference theory states that the lack of visual experience results in abilities which are qualitatively different from, but functionally equivalent to those of sighted people. Different experiments—including Fletcher's (1980) study—have rejected the deficiency theory. These experiments demonstrated that sighted participants perform in general better than visually impaired participants but that some visual impaired participants perform as well as the sighted. Gaunet and Briffault (2005) underlined a high variability in spatial skills among the group of visually impaired people. It is still difficult to validate either the inefficiency or the difference theories, as empirical evidence exists for both theories (Ungar, 2000). Recent studies favor the difference theory. For instance, Thinus-Blanc and Gaunet (1997) observed different behavioral strategies. Cattaneo and Vecchi (2011) proposed that visually impaired people can acquire spatial skills through compensatory task-related strategies and training. Cornoldi, Fastame, and Vecchi (2003) argued that congenital absence of visual perception does not prevent from processing mental images. However, these mental images are expected to be organized differently. In a recent study the cortical network of blind and sighted participants during navigation has been observed with functional magnetic resonance imaging (fMRI). Results suggest that blind people use the same cortical network— parahippocampus and visual cortex— for spatial navigation tasks as sighted subjects (Kupers, Chebat, Madsen, Paulson, & Ptito, 2010).

II.2.2.2 Differences between Spatial Cognition of Sighted and Visually Impaired People

Perceptual differences between sighted and visually impaired people result from the functional differences of the senses (see II.1.3). Vision in contrast to other senses allows to perceive a large environment in a short time (Cattaneo & Vecchi, 2011). The perception of a large-scale environment—through eye movements and reconstruction of the whole—demands as much cognitive effort from a sighted person as the haptic perception of a small-scale environment from a visually impaired person. Vision provides a spatial reference frame, i.e. objects are related to each other within the outlines perceived by the observer. It is harder to construct a reference frame by touch because tactile perception is serial and because touch requires direct contact. This problem is especially valid in a large-scale environment where objects are distant from one another. In comparison, in a small-scale environment it may be possible to introduce a reference frame, an orientation system, in which objects are located. We will refer to this as haptic reference frame in the remainder of the thesis. In addition, extraction of spatial properties of the surrounding world is more precise based on the visual sense (Thinus-Blanc & Gaunet, 1997). Many sources of sound are moving objects and thus harder to localize. Vision is more precise in the perception of shape than audition and also more precise for estimation of distance and direction. Besides, vision gives feedback about the perceptual consequences of a person's displacement. Continuous spatial updating is more cognitively demanding for visually impaired people (Cattaneo & Vecchi, 2011). Passini and Proulx observed that during navigation, visually impaired people made more decisions than sighted people (1988). Besides, landmarks used by the sighted may be irrelevant for visually impaired people (Gaunet & Briffault, 2005).

Quantitative advantages for vision over other senses (precision, greater amount of available information as described above) appear to introduce qualitative differences in encoding spatial information (Thinus-Blanc & Gaunet, 1997). In this respect early-blind and late-blind are often regarded separately (see II.1.2.2). Indeed, many studies show that congenitally blind and early blind are more impaired when performing spatial cognition tasks than late blind and sighted people. This suggests that vision plays an important role in setting up a spatial-processing mechanism. However, once the mechanism is established—as is the case for late blind—it can process information from other modalities (Thinus-Blanc & Gaunet, 1997). Visually impaired people perceive space sequentially from a body-centered perspective and have difficulties in processing information simultaneously (Cornoldi et al., 2003; Thinus-Blanc & Gaunet, 1997). Accordingly, several studies have demonstrated that congenitally and early blind people tend to code spatial relations in small-scale space in an egocentric rather than allocentric representation (Ungar, 2000). This perspective even persists after a time delay, whereas for sighted people a switch from egocentric to allocentric representations happens (Cattaneo & Vecchi, 2011). In relation to this, cardinal directions and Euclidian distances can pose difficulties (Gaunet & Briffault, 2005). Yet, congenitally and early—blind participants do have the potential to use allocentric coding strategies, but these strategies are more cognitively demanding (Cattaneo & Vecchi, 2011; Thinus-Blanc & Gaunet, 1997; Ungar, 2000). Most studies agree that early-blind perform as well as late-blind and sighted people in tasks that involve spatial memory, but less well in tasks involving spatial inference and mental rotations (Cattaneo & Vecchi, 2011; Thinus-Blanc & Gaunet, 1997). Early-blind have demonstrated problems updating spatial information when the perspective changes. This might result from different brain structures, from less experience with mental rotations—and consequently a lack of adapted strategies—or from the predominant egocentric representation (Cornoldi et al., 2003; Ungar, 2000). However, studies are controversial depending on the degree of rotation, complexity of the environment and individual strategies (Cattaneo & Vecchi, 2011). Cornoldi et al. compared spatial cognition with or without blindness for configurations of different sizes, with different length of pathways and in 2D and 3D conditions. Their results demonstrate that blind and sighted can generate and process a sequence of positions. However, they experience more problems in 3D environments. Also they face more problems when the length of the pathway is increased. They also observed that performance of the blind could be improved by using experimental material that they know better.

II.2.2.3 Factors Accounting for Discrepant Data

As stated before studies are controversial. In most studies significant differences between different groups were found but in some studies blind people did not perform significantly lower than sighted people.

Experimental factors can be a reason for discrepant results (Thinus-Blanc & Gaunet, 1997). First, the complexity of spatial information influences the results. The type of exposure to space (maps or direct exploration) also influences results. Another factor is the type of externalization of spatial knowledge, as for instance direct walking, pointing or sketch mapping. It makes a difference whether egocentric or allocentric representations are tested (Cattaneo & Vecchi, 2011). Results also vary depending on the subjects' familiarity with the experimental area, as this determines whether spatial memory or inferential abilities are evaluated (Thinus-Blanc & Gaunet, 1997). Then it also depends on whether spatial knowledge is acquired actively or passively. Results also vary depending on whether children or adults are tested. Visually impaired adults in contrast with children have acquired compensatory strategies (Cattaneo & Vecchi, 2011). Finally, Thinus-Blanc and Gaunet suggest that the size of the group and criteria of matching the participants within the group are important. In some studies participants within the same experimental group show totally different performance levels.

This leads to the second possible source of discrepancy: the blind represent a very heterogeneous group with a variety of inter-individual differences, such as age at onset and duration of blindness, etiology, mobility skills, braille reading skills and use of assistive technology (Cattaneo & Vecchi, 2011). It is extremely difficult to evaluate and control the influence of factors related to the subjects' personal histories (Thinus-Blanc & Gaunet, 1997). As discussed before, age at onset of blindness seems an important factor. For instance, Fletcher (1981a) observed that late blind children performed better than early blind children. However, different studies use different classification for early-blind (either before age 1 or age 3), therefore making it difficult to compare results. Congenital blindness may lead to delayed development of sensorimotor coordination (Thinus-Blanc & Gaunet, 1997). The etiology of blindness is another important factor. To this end, Fletcher (1981a) observed lower spatial performance with subjects attained with retinopathy of prematurity (ROP, see VII.2.11). ROP occurs mostly due to excessive oxygen given to prematurely born babies. Consequently, Fletcher suggested that the observed spatial impairment might be caused by overprotective parents who limit their children's spatial exploration. Depending on etiology and age at onset of blindness psychological reactions to the onset of blindness may include depression, autism and stereotyped behavior patterns (Thinus-Blanc & Gaunet, 1997). Another important factor concerns differences in locomotion training. Incoherence in studies might result from the effect that recently blind people have access to better training (Cattaneo & Vecchi, 2011). Fletcher (1981a) also observed a positive influence of intelligence—defined as brightness, thinking skill and reasoning ability—on spatial results. It can be assumed that today in contrast to earlier generations at least in our Western societies, visually impaired people have better access to education. Finally, socio-cultural factors also impact results (Cattaneo & Vecchi, 2011).

II.2.2.4 Strategies for Exploring Space without Vision

There is an ongoing debate whether and how behavioral strategies influence the performance level of spatial cognition. To this respect, several researchers have been investigating order and patterns of spatial exploration by visually impaired people. These studies have either been done in manipulator space (e.g., exploring a small-scale model or map) or in locomotor space (exploring a real environment). Fletcher (1981b) observed visually impaired children both while exploring a small-scale model and while exploring a real environment. She identified four strategies: 1) unsystematic exploration, 2) systematic clockwise exploration, 3) systematic counterclockwise exploration, 4) systematic exploration of opposites and diagonals. In the first trial the systematic counterclockwise exploration was the most successful. It corresponded to the direction in which the subjects were led by the experimenter during the familiarization phase. In the last trial differences between strategies had diminished. However, she observed a small but non-significant disadvantage for unsystematic exploration. Thinus-Blanc and Gaunet (1997) distinguish "back-and-forth patterns" and "cyclic patterns" for exploration both of manipulator and locomotor space. The first strategy corresponds to repeated movements between objects. It fosters a precise estimation of distance and angle relationships. The second strategy corresponds to a perimeter exploration that helps learning an overall configuration. They report that the best performers used a wide range of strategies. A predominant use of cyclic patterns leads to poor performance. Recently, Simonnet and Vieilledent (2012) observed blind sailors during the exploration of a virtual haptic and auditory maritime environment. They observed the use of five patterns: 1) "back-and-forth patterns" as reported by Thinus-Blanc and Gaunet; 2) "cyclic patterns" as reported by Thinus-Blanc and Gaunet; 3) "point of reference patterns" (star-shaped pattern): participants returned to a central point of interest and visited further objects from there; 4) "perimeter patterns": following the physical outline of the virtual workspace; 5) "grid patterns": repeated displacements of the cursor along straight parallel lines followed by displacements still along straight parallel lines, the second series of displacements being perpendicular to the first one. Participants used the strategies to different degrees, depending on whether they were asked to investigate or memorize the environment. Better accuracy and coordination were obtained when participants used the "central point of reference" strategy. As a conclusion, findings suggested that spatial cognition can be improved when exploration is systematic, and especially when a variety of patterns are employed. Yet, further investigations are necessary.

II.2.2.5 Measuring Spatial Knowledge

A variety of spatial orientation tests exist for measuring spatial knowledge. Ungar (2000) distinguishes between memory and inferential tasks. Memory tasks are questions based on a spatial relation that a participant has experienced before. They demand spatial coding. Inferential tasks require participants to infer a new spatial relation based on the environment they have explored before. They require a transformation from coded information. Likewise, Bosco et al. (2004) distinguished passive (memorization) versus active (transformation and manipulation) tasks. They further differentiate sequential and simultaneous processes.

Bosco et al. (2004) developed a battery of spatial tests. For evaluating different aspects of spatial orientation, they combined active and passive tests as well as simultaneous and sequential tests. Landmark tests were based on passive and simultaneous processing. Survey tasks combined all four types of processes. Route tests required essentially passive and sequential processing, but the need to update information required also active processing.

However, many spatial orientation tests are largely based on the visual sense—for drawing or recognition of scenes—and are therefore not adapted for use with visually impaired subjects. It is indeed difficult to design memory tasks that are adapted to measure spatial memory of the blind (Cornoldi et al., 2003). Miao and Weber (2012) proposed an evaluation method for cognitive maps of blind people. They let users model a labyrinth layout after exploration of this labyrinth. Then, they analyzed the model based on four main criteria: number of elements, property of streets, arrangement of streets and number of errors. Also they weighted the criteria following the importance that the visually impaired users had attributed them. However, this method was not adapted for more complex environments as it did not include knowledge on points of interest, curved streets and crossings.

Kitchin and Jacobson (1997) presented a classification of spatial orientation tasks adapted for visually impaired people. Some of the tests have been specifically developed for visually impaired people; some have been adapted by using alternative modalities to vision. Yet, this classification was not exhaustive. Whereas Bosco et al. proposed tests for evaluating landmark, route and survey knowledge, Kitchin and Jacobson only proposed tests for route and survey knowledge. Bosco et al. introduced two sets of landmark questions: landmark recognition and landmark surrounding recognition. Both were based on identifying the correct picture within a selection of pictures and thus purely visual.

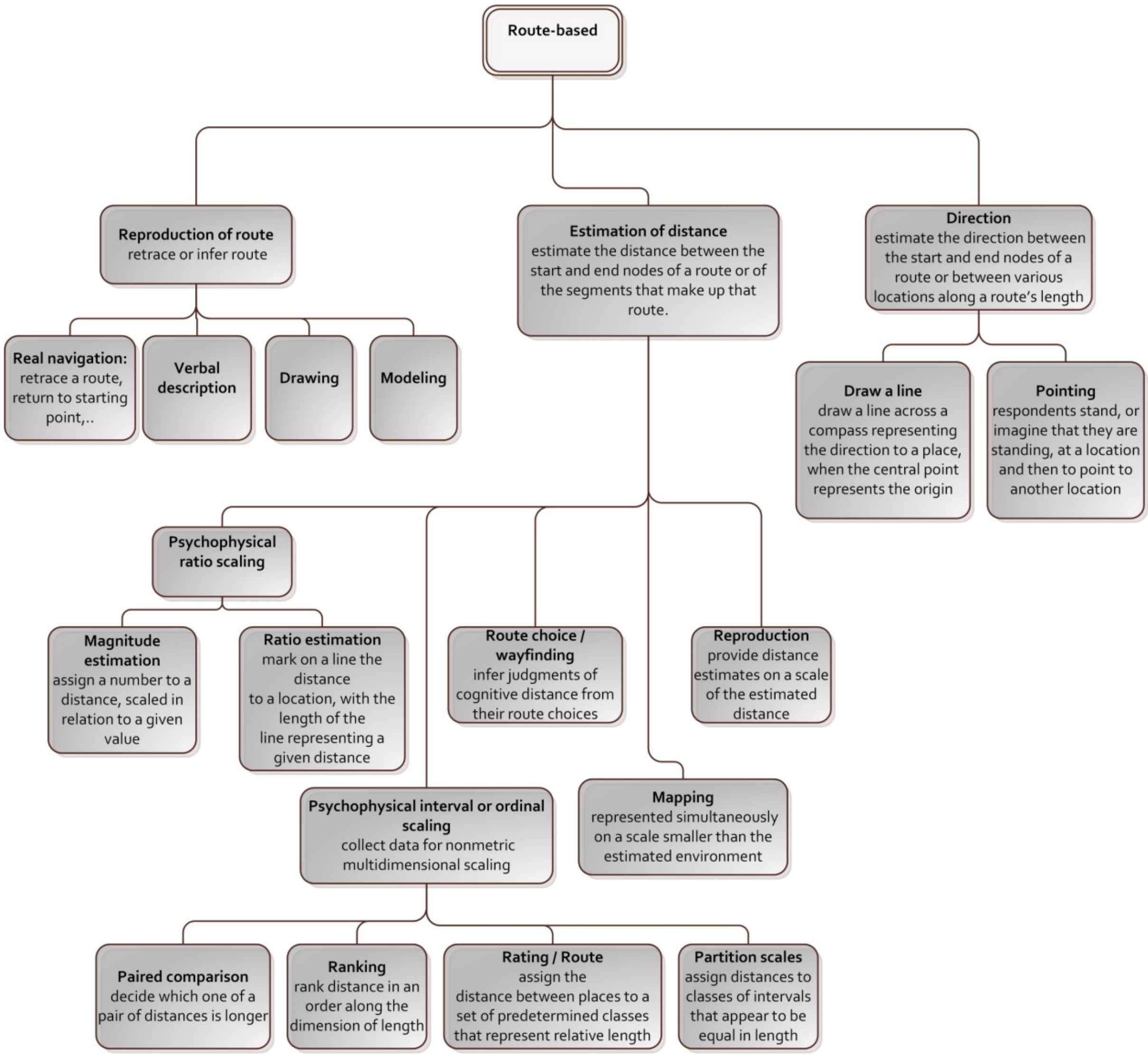


Figure II.2: Diagram of methods for evaluating route knowledge of visually impaired people as proposed by Kitchin and Jacobson (1997).

Route-based techniques determine participants' knowledge on how to travel between points of interest. Kitchin and Jacobson (1997) proposed several methods for evaluating route knowledge. We depicted the proposed methods as a diagram (see Figure II.2). Kitchin and Jacobson differentiated three main categories: reproduction of route (retrace or infer a route), estimation of distance between start and end notes of a route and direction estimation between start and end notes of a route. Bosco et al. (2004) proposed three tests in their test battery : 1) route recognition : participants had to identify the correct description of pathways between landmarks, 2) Wayfinding: participants followed a described pathway and finally indicated the arrival point choosing the correct one among three alternatives, 3) Route distance judgment: evaluating the route distance between a designated landmark and other positions.

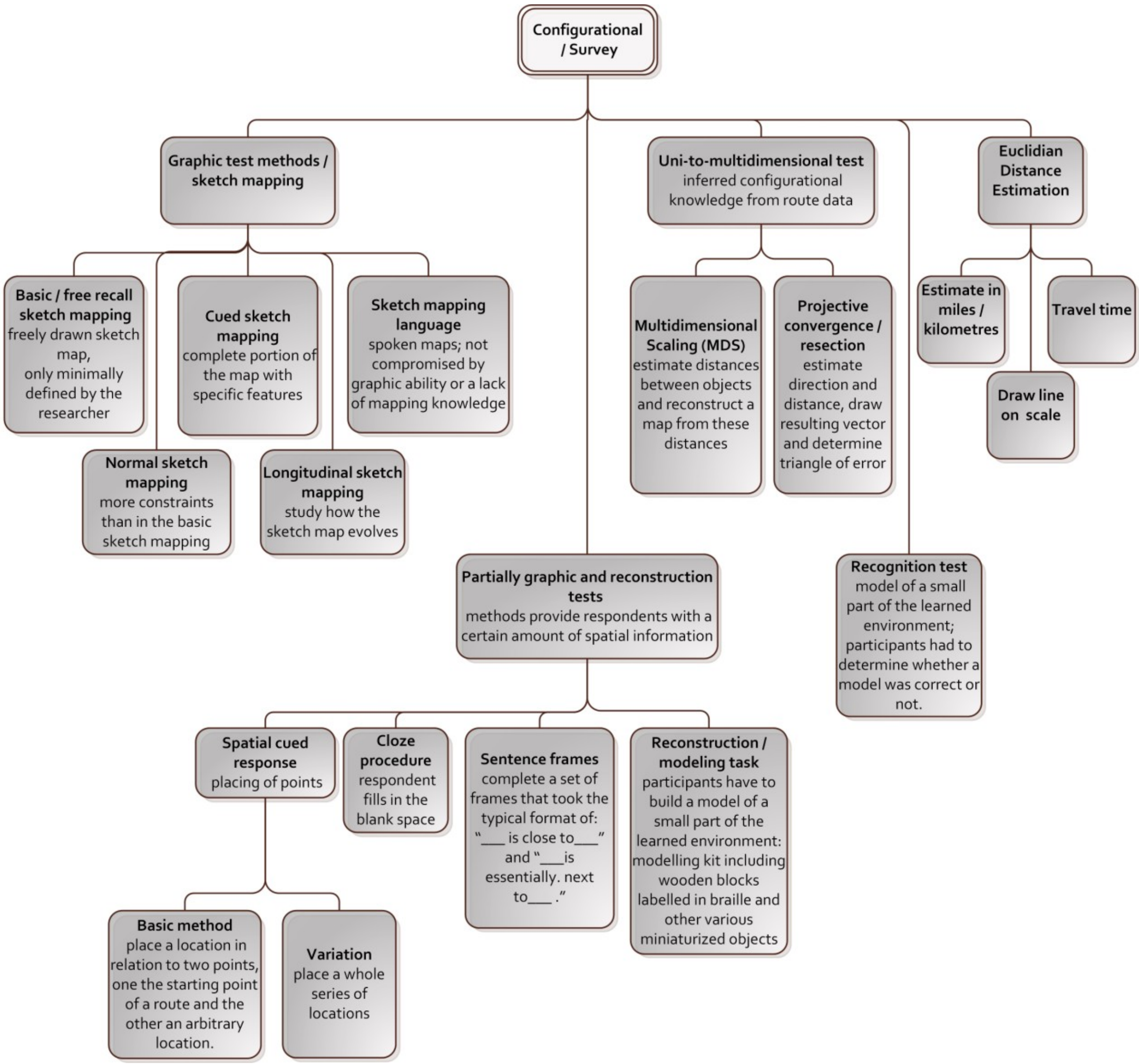


Figure II.3: Diagram of methods for evaluating survey knowledge of visually impaired people as proposed by Kitchin and Jacobson (1997).

Configurational or survey tests evaluate knowledge of the spatial relation between landmarks. Figure II.3 shows methods for evaluating survey knowledge as proposed by Kitchin and Jacobson (1997). They differentiated four main methods: 1) graphic test methods—also called sketch mapping, 2) partially graphic and reconstruction tests—methods that provide subjects with a certain amount of spatial information that has to be completed, 3) uni-to-multidimensional test that require participants to infer configurational knowledge from route information, 4) Euclidian distance estimation[4]. In comparison, Bosco et al. (2004) proposed three tests which are map completion (positioning landmarks in an empty map), map section rotation (different spatial relations were represented and users had to identify the correct solution), and finally Euclidian distance judgment.

Due to methodological biases, different spatial tests result in different scores (Kitchin, 1996). Also, visually impaired users might have shortcomings with one specific test, while they might be at ease with another test evaluating the same kind of knowledge. It is therefore recommended to use multiple, mutually supportive tests for evaluating spatial knowledge (Kitchin & Jacobson, 1997; Kitchin, 1996). This provides participants with the chance to compensate for shortcomings on one specific type of question. For instance, Picard and Pry (2009) observed that users had more problems with a modeling task than a recognition task where both were evaluating configurational knowledge.

Furthermore, sketch mapping is challenging for visually impaired users and is therefore often not used in tests with this user group (Kitchin & Jacobson, 1997; Ungar, 2000). Ungar (2000) reported that when asked to draw a map congenitally blind people had the tendency to linearize curved paths and that the maps were segmented and chunked rather than integrated. It may be easier to evaluate spatial knowledge with kits for construction small scale models (Blades, Lippa, Golledge, Jacobson, & Kitchin, 2002; Lahav & Mioduser, 2008; Passini & Proulx, 1988). Alternatively, methods that are based on oral descriptions are supposedly easier than methods that require drawing. Another advantage of asking questions is that it measures the spatial representation, whereas for drawing motor memory may be involved (Lederman & Klatzky, 2009). Finally, it has to be noted that the repetitive exposure to spatial tests may improve spatial skills (Blades et al., 2002). This must be considered in the test design.

A different kind of test is used for self-evaluation of spatial knowledge. The "Santa Barbara Sense Of Direction Scale" (SBSOD, Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002) proved to be internally consistent and had good test–retest reliability. It consists of 15 questions related to orientation and traveling. Examples are "I very easily get lost in a new city" or "I have trouble understanding directions". About half of the questions are each formulated positively or negatively. The SBSOD has been used in

[4] This method has been classified as route-based technique by Kitchin & Jacobson (1997). In contrast, Bosco et al. (2004) classified it as configurational method. We follow the latter as we believe that Euclidian distance in contrast to functional distance is part of configurational knowledge.

previous studies (see or instance Ishikawaa et al., 2008; Pielot & Boll, 2010). An alternative is the "Everyday Spatial Questionnaire" (Skelton, Bukach, Laurance, Thomas, & Jacobs, 2000). It consists of 13 questions that are very similar to those from the SBSOD. Examples are "Do you get lost when you go into large buildings for the first time?" or "Do you stop and ask for directions when you are on your way to some place?" In comparison with the SBSOD, more questions are investigating whether the respondent gets lost in an unknown place. The SBSOD seems to have questions of a higher variety of content.

To sum up, when measuring spatial knowledge of visually impaired people it is important to choose adapted tests that do not demand the use of the visual sense. It is recommended to choose more than one test for measuring the same spatial skills. It is also possible to let participants self-evaluate their spatial skills.

II.3 Maps as Tools for Spatial Cognition (without Vision)

As stated in the previous section, spatial representations can be acquired from direct experience as well as from symbolic representations. In this section we present different tools that can help create a mental representation of space, with a specific focus on maps. We will then give an overview of maps for visually impaired people and how these maps can be created.

II.3.1 Tools for Improving Mobility and Orientation

Ideally, travel should be as independent, efficient, safe, and relaxed for visually impaired people as for sighted people (Jacobson, 1996). In reality, mobility and orientation are challenging for visually impaired people. Tools for improving orientation and mobility skills can help overcome fear related to travel. These tools include Electronic Travel Aids (Loomis, Golledge, Klatzky, & Marston, 2007), maps and images (Jacobson, 1996), 3-D models (Picard & Pry, 2009), and verbal descriptions (Gaunet & Briffault, 2005; Roger et al., 2011). Different tools can be classified in two main categories. Either these tools are used during the journey, or prior to the journey with the purpose of creating a cognitive map. Lahav and Mioduser (2008) called the first category "dynamic devices" and the latter "passive devices".

Electronic Travel Aids (also called Electronic Mobility Aids) are normally used during traveling. They can further be distinguished in devices "sensing immediate environment" —such as electronic white canes—and "navigation" devices—such as GPS systems (Loomis et al., 2007). As our focus is on acquisition of spatial knowledge prior to traveling, we will not further detail Electronic Travel Aids in this thesis. Recent reviews were presented by Kammoun (2013) and Roentgen, Gelderblom, Soede, and de Witte (2008).

Verbal descriptions can be helpful for the acquisition of mental maps as well as during the traveling. In general, verbal descriptions are based on natural language. They require an automatic system or a guide who has more spatial knowledge of the environment than the guided person. Information indicated by language is either qualitative or quantitative and imprecise (Montello, 2001). Statements about pathway connections and approximate location are more important than precise distance or direction estimation. For example, most people would have more problems interpreting "turn left after 400 m south east direction" than "turn left at the next crossing". Concretely, Roger et al. (2011) studied the role of landmark information in speech-based over-the-phone guidance systems for sighted people. They observed that instructions containing landmarks enabled more efficient wayfinding, less error prone direction estimation and higher navigation performance. Besides, they were preferred by the participants. Very few studies investigated form, content, and functional information of route descriptions for blind people. Gaunet and Briffault (2005) proposed functional specifications for verbally guiding blind pedestrians in unfamiliar areas. They identified which information and instructions should be given and at which concrete location. Generally, it is a disadvantage of verbal guidance that the sense of the verbal descriptions depends on the speaker as a person, the speaker's location, the environmental context, the previous topic of conversation, etc. (Montello, 2001). For instance, Roger et al. (2009) observed in a study with sighted people that a person verbally guiding another one adapted to the guided person. They provided more landmark information when guiding a person without prior knowledge of the environment. Besides, depending on the guide's spatial abilities the landmark information was either provided in an egocentric or allocentric reference frame. Decoding these verbal messages is possible only with highly symbolized intellectual development (Siegel & White, 1975).

Small-scale models are three-dimensional representations of the environment. They are often used in touristic sites to give an overview of the environment. They can also be a helpful tool for visually impaired users. Picard and Pry (2009) studied the use of small-scale models for low-vision respectively blind adults (see Figure II.4). They observed that exploring a small-scale model was effectively improving spatial cognition—especially survey knowledge—independently of the level of visual impairment. In contrast, Fletcher (1981b) observed no significant effect between children that learnt a spatial environment from a model and those that learnt it through direct experience. However, the children had not had any training on map exploration prior to the experiment. A disadvantage of small-scale models is that they are costly in production and cumbersome for transportation.

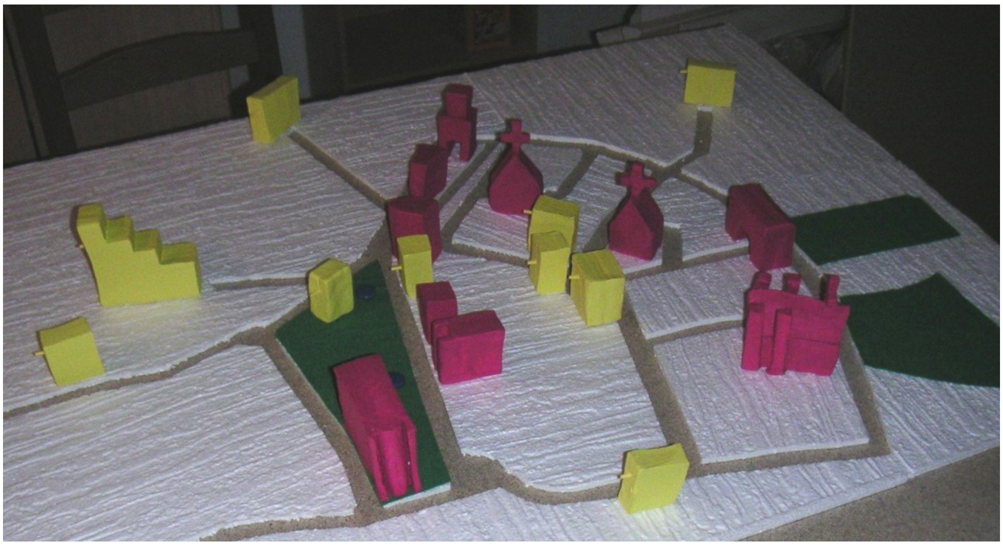


Figure II.4: Small-scale model for visually impaired people as presented by (Picard & Pry, 2009). Reprinted with permission.

II.3.1.1 Maps

Maps are representations of the environment that communicate information (Lloyd, 2000). They are two-dimensional, projective and small-scale (Hatwell & Martinez-Sarrochi, 2003). Maps are representations of space which are in themselves spatial. The environment is presented from an allocentric survey perspective. Maps differ from photographs in that a cartographer has arranged spatial information for communication (Lloyd, 2000). A map is thus a device for storing spatial information by a cartographer and a source of knowledge for the map reader.

Scale refers to the actual spatial extent that is represented in a map. Maps can have different scales, ranging for instance from a room to a representation of the entire globe (Hatwell & Martinez-Sarrochi, 2003). Another measure is granularity which characterizes the amount of detail that is offered (Klippel, Hirtle, & Davies, 2010).

Maps can have different purposes. Orientation and mobility maps provide the possibilities of exploring unknown areas, getting an overview about the surrounding of a landmark, localizing specific landmarks or preparing travel (Heuten, Wichmann, & Boll, 2006). The location of a particular place can be determined in absolute terms—latitude, longitude—or in relative terms—in comparison to a reference point (Lloyd, 2000). Besides, maps allow the estimation of distances and directions (Hatwell & Martinez-Sarrochi, 2003). Thus, map readers can connect objects and structures in their cognitive maps with objects and structures in the real world (Klippel et al., 2010). Edman (1992) further differentiated maps that are used for teaching geography, topological maps (maps based on few selected features, without necessarily respecting distance, scale and orientation) and thematic maps (maps giving qualitative or quantitative information on a specific topic). Cloropleth maps are specific thematic maps in which the shading of areas indicates the measurement of a specific variable (Zhao, Plaisant, Shneiderman, & Lazar, 2008).

Map representations are not perfect representations of the environment. Some deformations occur when the cartographer transforms spatial data into spatial information and other changes occur when the map reader transforms spatial information into spatial knowledge (Lloyd, 2000). Cartographers categorize, generalize and symbolize to underline important information and eliminate non-essential information. Important aspects for map design are that the most relevant details are easy to perceive, that it is easy to get an overview of the environment, that map readers can understand the position of landmarks and destinations, that the size and shape of map elements can be perceived and that distances and directions can be understood (Heuten et al., 2006).

One specific type of map is you-are-here (YAH) maps. YAH maps are reference maps showing features in the environment of the map reader (Montello, 2010). They normally include a symbol representing the location and possibly the orientation of a person viewing the map. YAH maps are always in situ, i.e. they represent the location in which they are placed. These maps intend to solve wayfinding problems for a person in a navigation situation.

Maps for visually impaired people are traditionally tactile—i.e., raised-line maps (see II.3.3). On a tactile map, information is presented through relief—raised lines—with the help of different lines, symbols and textures. Braille is used to add textual information. Tactile maps have proved to be useful tools for presenting survey knowledge. In this regard, tactile maps provide at least two important benefits (Ungar, 2000). In the short-term they introduce a person to a particular space, in the long-term they improve spatial cognition. Accordingly, they have been used both as wayfinding aids and as mobility learning aids in education (Jacobson, 1996). We will investigate this in more detail in a later section (II.3.2.2).

II.3.2 Map Reading and Cognitive Mapping

In the following subsections we discuss which cognitive processes are involved in acquiring spatial knowledge from maps, first for sighted, then for visually impaired people.

II.3.2.1 Cognition of Sighted Map Readers

Lloyd (2000) defined map reading as an integration and synthesis of knowledge through bottom-up and top-down processes. Bottom-up processes are based on the lines, colors, shapes and words contained in the map. Top-down processes are based on previous knowledge. It is possible that this previous knowledge has been acquired in another context but is applicable to maps, such as meaning of words or judging of distances. It can also be prior knowledge about maps and conventions, such as meaning of common symbols or conventional use of colors and shapes. More precisely, Lloyd (2000) distinguished declarative knowledge (e.g., meaning of symbols and color conventions), procedural knowledge (e.g., how to evaluate distances or elevation), semantic knowledge (e.g., meaning of categories), episodic knowledge (e.g., comparing maps from different time periods) and strategic knowledge (e.g., making map reading more efficient).

By learning the patterns on the map, spatial information represented on the map becomes spatial knowledge (Lloyd, 2000). In order to access the information from the map, map readers must possess the necessary perceptual and cognitive skills that allow access to embedded symbolic codes (Hatwell & Martinez-Sarrochi, 2003). On the perceptual level, they must first discriminate map elements and comprehend the general spatial structure. On the cognitive level, readers encounter several challenges. First, they must operate a transformation from 2D to the larger 3D space. Second, map readers have to project themselves into the map which includes finding one's position and rotation of the map if necessary. Third, directions, distances and landmarks have to be extracted and held in memory. The cognitive mapper thus simplifies the map information, that is already a simplified representation of the environment (Lloyd, 2000). The set of operations for encoding and decoding of the map is called the signature (Downs & Stea, 1973). Concretely, Downs and Stea define three operations as part of the signature: rotation of viewpoints, scale change and abstraction to a set of symbols.

Map reading is especially difficult in the case that rotation needs to be applied. This happens if the map and the heading of the reader are misaligned, i.e. not facing in the same direction (Thinus-Blanc & Gaunet, 1997). Conventionally, (YAH) maps are considered aligned when the "up" direction on a vertically-displayed map or the forward direction on a horizontally-displayed map correspond to the direction in which the map reader faces in the environment (Montello, 2010). (Mental) rotation of maps can result in orientation errors. The problem arises because spatial perception is "orientation-dependent" (Montello, 2001). The cost of time, error and stress resulting from the misalignment are denominated the "alignment effect". Maps can be misaligned by any angle, but not all degrees of misalignment produce an equal cost. Also, it appears that performance can be improved through practice. Concretely, Montello (2010) defines a four-step strategy that map readers apply in order to resolve misalignment. First, they must be aware of the misalignment. Second, they must determine the degree of misalignment. Third, they must determine an approach to either mentally or physically transform the orientation of the map or their own orientation. Fourth, they need to carry out this approach successfully.

II.3.2.1.a Impact of Different Orientation Tools on Cognitive Mapping

As stated above, maps are not the only tools that provide spatial knowledge. Spatial knowledge can also be acquired during direct exploration of the environment. It is interesting to investigate the differences between these different sources for creating cognitive maps.

Thorndyke and Hayes-Roth (1982) compared learning spatial knowledge from maps and direct experience. Direct navigation led to the acquisition of route knowledge (measured as orientation of the own body with respect to unseen objects and estimating route distances); map exploration led to the acquisition of survey knowledge (measured as judgments of relative location and straight-line distances). Furthermore, their study revealed that it is possible to acquire exact survey knowledge from extensive direct experience. However, it can be obtained more quickly and with less effort from map reading. Extensive map learning did not further improve performance.

Recently, studies have compared GPS-based navigation systems with maps and direct experience. Münzer, Zimmer, Schwalm, Baus, and Aslan (2006) compared acquisition of spatial knowledge from using a navigation system with map usage. Consistently with Thorndyke and Hayes-Roth they observed a better survey knowledge for map readers than for navigation system users. Although route knowledge was good in both conditions, it was significantly better in the map condition. They hypothesize that spatial knowledge of navigation system users is poorer, because being guided by a navigation system does not stimulate users to actively encode and memorize spatial information. In comparison, map usage encourages active learning as the route has to be kept in working memory. Ishikawaa et al. (2008) compared navigation guided by a GPS-based navigation system, by a map and navigation based on experience of walking routes accompanied by a person. Their results show that navigation system usage affects the user's wayfinding behavior and spatial knowledge differently than do the maps and direct experience. GPS-based navigation was less smooth than direct experience and map learning, i.e. participants made more stops, travelled further distances and took a longer time. Besides, route knowledge was acquired more precisely through direct experience than through navigation system usage. However, performance improved over time both for the navigation system and the map group.

To sum up, there is evidence that map use can improve spatial knowledge. Due to their allocentric layout, maps especially improve survey knowledge. Survey knowledge can also be acquired from direct experience but it takes more time and effort to do so. Finally, navigation systems seem to impoverish the acquisition of spatial knowledge.

II.3.2.2 Map Reading in the Absence of Vision

As discussed before, spatial cognition of visually impaired people differs from sighted people. Map reading without sight specifically demands the use of the haptic sense. Traditionally, maps for visually impaired people are tactile maps[5]. In a first step we investigate cognitive mapping from haptic exploration. Then, we will focus specifically on haptic exploration of visually impaired people.

II.3.2.2.a Reading of Tactile Images

Identifying tactile images has often proved a hard task, even for sighted subjects. Touch is best adapted for exploring three-dimensional objects (Hatwell & Martinez-Sarrochi, 2003). Tactile maps and images in the form of raised-line drawings vary from real-life objects in shape and volume as they only depict contours (see Figure II.5). Also material properties—such as texture, compliance or temperature—are missing as cues for the identification of objects. The identification of objects depicted in raised-line pictures has proved more difficult than the identification of real objects. This was valid even if the detection of material properties of real objects was impoverished by wearing gloves (Klatzky, Loomis, Lederman, Wake, & Fujita, 1993). To this end, Hinton (1993) proposed that including 3D information—such as texture, convex or concave surfaces—in tactile diagrams can be helpful.

Figure II.5: A visually impaired person reading a tactile map.

[5] More recently audio maps or maps combining audio and tactile output emerged. See II.3.4.

In general it has been observed that the short-term memory for tactile sense is less functional than for vision. However, this advantage for the visual sense vanished when vision was limited to a small aperture (Picard & Monnier, 2009). Based on this finding it can be hypothesized that disadvantages for the tactile sense regarding identification of structures are due to the serial character of touch—as compared to vision that is quasi parallel. Wijntjes, Van Lienen, Verstijnen, and Kappers (2008a) observed sighted people exploring raised-line drawings. Participants had memorized the outlines correctly and were able to draw them, but could only identify them visually when seeing their drawing. They conclude that mental capacities required for identification of raised-line drawings were inadequate.

Various studies observed sighted people during the exploration of raised-line pictures. Picard and Lebaz (2012) compared 16 studies investigating identification of raised-line drawings of everyday objects by sighted and visually impaired people. Independently of the visual capacities, they identified several factors that played an important role for performance in tactile image identification. Among these criteria is the size of the picture, with a larger image size improving recognitions scores. Also, prior semantic knowledge about the context of the image improved picture recognition. Then, there was a significant effect of the paper type used for production of the tactile images (see also II.3.3.1.b). Furthermore differences in performance were related to haptic exploration strategies. Guided exploration enhanced accuracy. Accuracy was also improved when more than one finger or hand could be used for exploration (see II.3.2.2.b for more details).

Another criteria that influenced tactile image recognition is the complexity of the image (Hinton, 1993). The more complex the drawings, the longer the response times and the lower the accuracy and response rates (Lebaz, Jouffrais, & Picard, 2012). Raised-line drawings themselves are two-dimensional but they may represent objects either in a 2D or 3D perspective (Lebaz et al., 2012). It has been observed that raised-line drawings depicting 3D objects are more difficult to identify than those depicting 2D objects (Picard & Lebaz, 2012). Participants in a corresponding study were faster at identifying objects when they identified 2D drawings than 3D images. This result was valid independently of visuo-spatial capacities (Lebaz et al., 2012). It might be hypothesized that 3D raised-line images place higher demands on visual imagery. Lebaz et al. (2012) argued that 3D raised-line images place higher demands on haptic exploration and on the parsing of the drawing into significant representational units. This might be due to the fact that the strategy of contour following (Lederman & Klatzky, 2009) does not prove effective in the case of 3D objects because of the perspective included in the drawing.

Visuo-spatial imagery also influences the identification of raised-line drawings. In a study by Lebaz et al. (2012) sighted adults with high visuo-spatial capacities outperformed low visuo-spatial imagers on accuracy, but not on response times. The same finding is confirmed in another study by Picard, Lebaz, Jouffrais, and Monnier (2010).

Furthermore, different studies have proved that tactile picture identification and haptic memory span improve with age from childhood to adulthood (see for instance Picard, Albaret, & Mazella, 2013; Picard & Monnier, 2009). The developmental curve for tactual-spatial learning was measured as parallel to the developmental curve for visual-spatial capacities (Picard & Monnier, 2009).

Studies on identification of raised-line drawings and maps by blind people revealed contradictory findings concerning the impact of the visual status on the performance (Picard & Lebaz, 2012; Thinus-Blanc & Gaunet, 1997). For instance, in a haptic identification task comparing early blind, low vision and sighted children, low-vision children outperformed the two other groups (Vinter, Fernandes, Orlandi, & Morgan, 2012). On the other hand, in a study with early blind, late blind and blindfolded sighted adults, participants demonstrated good discriminability in the tactile-patterns recognition task regardless of their visual status (Picard et al., 2010). As argued before these contradictory findings may result from inter-individual differences (see II.2.2.3). It has also been argued that the difficulties of some blind people concerning identification of figurative drawings might be related to difficulties in interpreting visual drawing conventions rather than inefficient haptic exploration or encoding in the memory (Picard et al., 2010). Besides, different task requirements have an impact on the observed influence of visual status on performance (Postma, Zuidhoek, Noordzij, & Kappers, 2007). Picard et al. (2010) observed early blind, late blind and blindfolded sighted people. They discovered that multiple forms of memory strategies are used including visual imagery, spatial imagery, kinesthetic imagery, verbal recoding of the patterns and combinations of these strategies. All early blind used non visual strategies, whereas late blind used both visual and non-visual strategies and sighted used mainly visual strategies. They did not observe any impact of these strategies on identification performance.

II.3.2.2.b Haptic Exploration of Tactile Images

As reported previously (see II.2.2.2), it is much harder to perceive a spatial reference frame during tactile exploration than during visual exploration of space. Tactile maps typically provide a haptic reference frame through the physical limits of the map. Alternatively, the outline of the reference frame can be marked as raised-line on the map.

Strategies for exploring tactile images are important as they may influence performance. We present different studies on raised-line map exploration in detail in subsection V.1.1. In brief, some studies have investigated whether the number of fingers implied in haptic exploration has an impact on tactile image recognition. Findings suggested that increasing the perceptual field by using more than one finger improved raised-line picture identification. Besides, it seems that blind people have an advantage over sighted people with regard to the use of systematic exploration strategies. It can be hypothesized that the same is valid for raised-line maps, even if this has so far not been investigated. To confirm the validity of findings on haptic exploration for tactile maps, there is need for further investigations.

II.3.2.2.c Tactile Maps and Spatial Cognition

Some studies specifically investigated the benefits of tactile maps for visually impaired adults. Jacobson (1992) demonstrated that tactile maps can be useful to improve the spatial knowledge of a familiar environment of visually impaired adults. He first let three visually impaired people draw a sketch map of the campus of the university college of Swansea, a familiar environment. Afterwards, participants were familiarized with a tactile map of the campus. One week later, they had to redraw the sketch map. As a result the final map drawings included far more campus description and details than the initial sketch maps.

In another study, Jacobson and Kitchin (1995) let three visually impaired adults study a tactile map of the area they lived in. Participants had to respond to three different tests afterwards. They failed in estimating relative distances between towns. On the contrary, they succeeded in locating towns on a partially complete tactile map and in determining which map out of a set of three was correctly oriented despite the map being rotated. In a follow-up study, Jacobson (1998b) compared spatial knowledge acquisition between two groups of visually impaired adults. A first group learnt spatial knowledge by walking a route with a mobility instructor. A second group explored an audio-tactile map before walking the route with a mobility instructor. Both groups then had to walk the route unaided. Afterwards they were asked to draw a sketch map of the route and to describe the route in as much detail as they remembered. The resulting sketch maps proved to be more accurate for the group that had explored the audio-tactile map.

Two experiments were conducted by Espinosa, Ungar, Ochaita, Blades, and Spencer (1998). In a first experiment, thirty visually impaired adults learnt a complex and unfamiliar route either by direct experience, by direct experience while carrying a tactile map, or by direct experience accompanied by a verbal description of the area.

Afterwards, participants had to walk the route unaided. As a result, participants who learnt the route from a combination of direct experience and tactile map reading proved a gain in spatial knowledge of the environment—both practical and representational—than those in the two other conditions. In a second experiment, Espinosa et al. investigated whether learning a route from a tactile map before having any direct experience of the environment facilitates acquisition of spatial knowledge in comparison with direct experience of the route. Ten visually impaired adults learnt an unfamiliar route either by direct experience or through map learning. Participants performed just as well after exploring a tactile map as they did after direct experience in the environment. This finding demonstrates that tactile maps are an effective means for introducing blind and visually impaired people to the spatial structure of a novel area.

Caddeo, Fornara, Nenci, and Piroddi (2006) found similar results. They observed visually impaired adults learning a novel route either by using tactile maps and direct experience or direct experience with verbal descriptions. The participants who had access to the tactile map showed better performance in walking time and deviation from the route. Some studies demonstrated that tactile maps are more suitable tools for presenting spatial knowledge to blind people than verbal descriptions (Cattaneo & Vecchi, 2011). This might be due to a higher working load for verbal information.

Similar results have been found, when studying tactile map use for visually impaired children. In a study by Ungar, Blades, Spencer, and Morsley (1994) visually impaired children, aged between 5 and 11, learnt the outline of familiar toys on the floor of a large hall either by direct experience or by a tactile map. Totally blind children in this study learnt the environment more accurately from the map than from direct exploration. Ungar and Blades (1997) compared tactile map usage by visually impaired children (again aged 5 to 11 years) and sighted peers for inferring distances. Visually impaired children's performance was lower than that of sighted control, but after instructions on how to infer distance from a map, their performance improved. Wright, Harris, and Sticken (2010) compared differences in studies on tactile map learning for visually impaired children. They observed that studies obtained contradictory findings on the influence of chronological age and the amount of residual vision on results, but that teaching efficient map reading strategies appeared as an important factor.

To sum up, tactile maps help visually impaired adults as well as children to acquire spatial knowledge of familiar and novel environments. Tactile maps preserve relations between landmarks in space but present those relationships within one or two hand-spans (Ungar, 2000). Thinus-Blanc and Gaunet argue therefore that exploration of a tactile map demands a smaller working load than exploration of a real environment. Also they outline that during exploration of manipulator space, it is possible to keep a fixed reference point, whereas during exploration of locomotor space the participant is moving and so is the reference system (the own body). Besides the tactile map is simplified in content and therefore free from noise that is present in the environment (Ungar, 2000). Ungar (2000) also underlined that exploration of locomotor space may be subject to fears related to traveling, whereas exploration of maps can be done without danger and anxiety. Therefore it can undoubtedly be concluded that maps are an important tool for improving spatial cognition of visually impaired people.

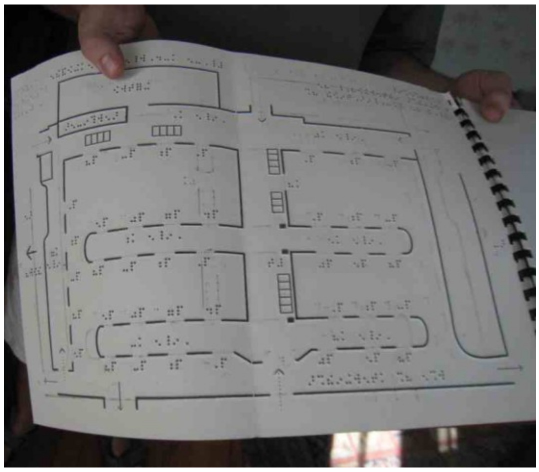
II.3.3 Design and Production of Tactile Maps

For the design of tactile maps several aspects have to be considered. We will present these aspects in the following subsections. First, we present different production methods for tactile maps. Second, we discuss how the map drawing has to be designed in order to respect rules and guidelines imposed by the perceptual limits of the tactile sense. Finally, we investigate the limits of these maps for presenting spatial knowledge to visually impaired people.

II.3.3.1 Production of Tactile Maps

Many methods exist for producing tactile maps and images. We present an overview of different techniques in the appendix (VII.4.1). In this paragraph we will only compare vacuum-forming and swell-paper as they are the most common techniques for the creation of tactile maps and images.

(a)



(b)

Figure II.6: Different production methods for tactile maps. (a) Vacuum-formed map of Europe. (b) Swell-paper map of a bus terminal

Vacuum-forming (see Figure II.6 a), also called thermoforming, is a technique that allows reproduction of several images from the same master. Concretely, a master can be produced from various material (Edman, 1992). Once the master established, a sheet of plastic is placed on the master in a specific machine and heated while evacuating the air. The sheet is thus permanently deformed. With this method it is possible to create recessed lines as well as several levels of height, which can improve readability of the image (Edman, 1992). On the downside its production is costly and special equipment is needed (Tatham, 1991).

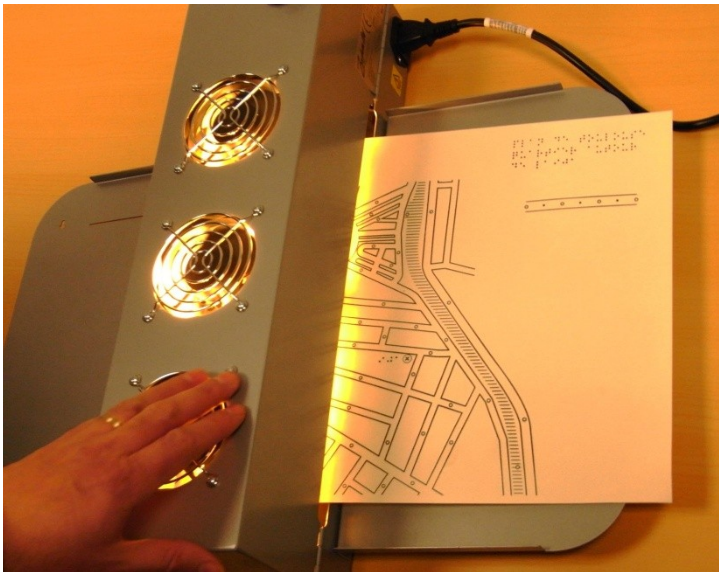


Figure II.7: Production of swell-paper maps. A swell-paper map is passed through the heater.

Swell paper—also called microcapsule paper or heat sensitive paper (see Figure II.6 b) works with a normal printer, special paper and a heater (Figure II.7). The map is printed on paper that contains microcapsules of alcohol in its coating. As the black ink absorbs more heat, the capsules of alcohol expand when the paper is passed in the heater (Edman, 1992). The production method is easy and costs are lower than for vacuum forming (Lobben & Lawrence, 2012). The printer is a normal inkjet printer or copying machine and the paper is sold at around 1€ per sheet. Only the heater is specific hardware which is more costly. Images can be prepared using a computer and it is easy to reprint the same image. The resulting image is perceivable both by the tactile and the visual sense, therefore making it possible to share information between a visually impaired person and a sighted assistant. It is also possible to annotate a printed image with colors for a person with low-vision. A disadvantage is that tactile images created with this method are binary, i.e. the surface is either flat or raised and height cannot be modulated. Also corners are rounded and it is not possible to produced accurate angles

(Bris, 1999). Repeated touching may damage the relief and images can therefore lose their readability after a number of uses.

Perkins (2001) provided a comparison between production of tactile images with vacuum-formed paper and microcapsule paper. Groups of students were asked to produce maps of the campus of the University of Manchester with both technologies. Evaluations showed that the maps produced with the vacuum-forming were more precise. From a cognitive perspective, Picard and Lebaz (2012) analyzed different studies on tactile image recognition. They observed that swell paper images were recognized with a higher accuracy than images produced with a plastic sheet on a drawing board (VII.4.1).

II.3.3.1 Map Design

Tactile maps present information through relief in form of different lines, symbols and textures. Braille is used to annotate the map with textual information (Edman, 1992; Tatham, 1991). In the following subsections we present recommendations on tactile map design. A summary of these recommendations is given in the appendix (VII.4.2).

II.3.3.1.a Map Drawing

The design of tactile maps is challenging. An excessively detailed map is cluttered and unreadable, and results in a perceptual overload for the reader (Jacobson, 1996). This relates to the limitations of the tactile sense in comparison with vision as detailed in section II.1.3. Due to these limitations, tactile maps must be simplified representations of the symbolized space but still contain all useful and important information (Hatwell & Martinez-Sarrochi, 2003). To this end, Edman (1992) proposed to keep forms simple and without decoration. If visual maps are often made respecting a pleasant layout, for tactile maps it is more important that elements are readable and distinguishable than pleasing. Specifically, contrast is important (Edman, 1992; Tatham, 1991). Tactile contrast can be achieved using textures, shapes, sizes, orientations and spacing (Tatham, 1991).

Existing raised-line maps use various symbols and textures, and there are no strict rules on how to design tactile maps. This lack of standardization makes the map reading more challenging for visually impaired people (Lobben & Lawrence, 2012). Attempts of standardization are described in the appendix (VII.4.2.1). In addition to these attempts, existing guidelines can be helpful for the design of tactile maps and images. Edman (1992) gives an exhaustive overview of current practices in the design and production of tactile maps and images. Paladugu et al. (2010) evaluated different tactile symbols with six blind participants. They measured rating, accuracy of naming streets and time for finding the symbols. Their study led to the proposition of a tactile symbol set. Other guidelines are specifically based on the perceptive constraints of the haptic sense (Bris, 1999; Picard, 2012; Tatham, 1991). For instance tactile acuity impacts the minimum and maximum distances between two lines. In the appendix we detail recommendations concerning lines, symbols and textures (VII.4.2.2). It is especially important to note that the number of elements on the map must be limited as much as possible, in order to avoid overloading the map reader with too much information. On one hand this concerns the total number of map elements. Picard suggested to display not more than 30 map elements in total (maximum 20 inside the map and 10 outside the map outline). She proposed to display not more than 2 elements per 2 cm^2 as this corresponds to the perceptive space of the fingertip moving laterally. On the other hand, the number of different symbols and textures that need to be differentiated should be limited. Tatham proposed to use not more than 8 to 10 different symbols. Bris defined the maximum as 3 to 5 different textures.

II.3.3.1.b Braille

Braille is a raised dot embossed alphabet. It has been invented by Louis Braille in 1824 and is today the international standard writing system for blind people. It is used in many countries, for text, music, mathematics and even computer science. Each letter in the alphabet is a rectangular cell composed by 6 to 8 points. A braille cell can be entirely covered by a fingertip (Cattaneo & Vecchi, 2011). Different versions exist such as contracted braille to speed up the reading process (Tobin, Greaney, & Hill, 2003). According to Hatwell (2003), braille is remarkably well adapted to the sensory capacities of the index finger. However she argues that it is challenging to learn it. Difficulties lie in the perceptual aspects, spatial aspects (no spatial reference frame exists), phonological and semantic aspects. Tobin et al. (2003) state three factors that make reading by touch more challenging. First, there is a higher demand on short-term memory as information must be memorized until sufficient information is available to permit “closure” and interpretation of the whole word or phrase. Second, the left to right scanning and location of the next line demand fine psycho-motor control. Third, the person needs to have enough motivation to continue reading despite the additional time required for decoding and assimilating the information. Braille reading speed depends on several factors, such as the age when braille reading skills are acquired. If braille is learnt at a younger age, a higher reading speed can be accomplished (Tobin et al., 2003). As a result, only a small part of the visually impaired population can read braille. In France 15% of blind people read braille and only 10% of them read and write it (C2RP, 2005). In the United States, fewer than 10% of the legally blind people are braille readers and only 10% of blind children are learning it (National Federation of the Blind, 2009).

Braille is the standard means of annotating tactile maps (Edman, 1992). However, including braille into tactile maps is challenging (Tatham, 1991). First, braille text needs a lot of space and therefore dominates what is on the map (Hinton, 1993). Second, it is inflexible in size, inter-cell spacing and orientation (Tatham, 1991). In comparison, text on visual size can be written in fonts of different size and style, it can be rotated to squeeze it in open spaces, upper and lower cases as well as color can be used to highlight important text. Braille lacks all of these possibilities. More concretely, the height of braille letters correspond to a normal font in size 26 points (Tatham, 1991). Because of a lack of space to include entire text lines on the map itself, normally a legend is used to display braille text (see Figure II.8). The use of a legend or key can make a map more readable. Yet, alternating between reading the map and the legend, disrupts the reading process (Hinton, 1993).

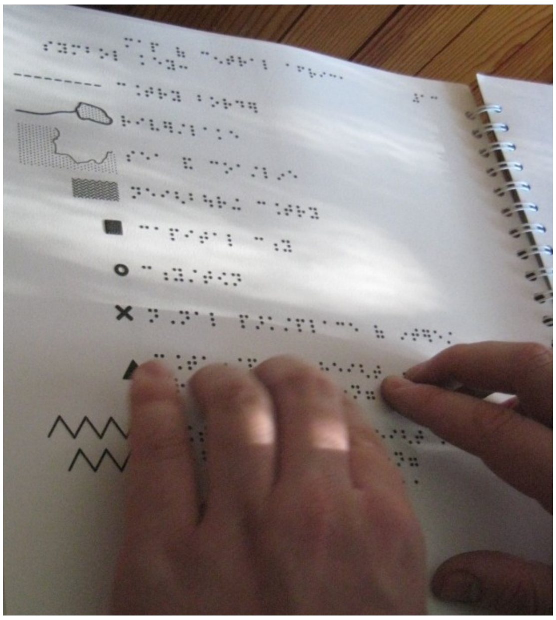


Figure II.8: Reading a braille legend that accompanies a tactile map.

To conclude, braille is an effective and widely spread means of making text accessible for visually impaired people. Yet, it cannot be presumed that all visually impaired people know how to read braille as it is cognitively challenging. Also it is not obvious to integrate braille text when designing tactile maps.

II.3.3.2 Limitations of Tactile Maps

Although tactile maps are efficient means for the acquisition of spatial knowledge, several limitations and problems are associated with them.

Some critique concerns the production of the map. Rice, Jacobson, Golledge, and Jones (2005) argued that the creation of tactile maps was very costly in time. They suggested that the automatic creation of maps from Geographic Information Systems (GIS) could speed up map creation. Besides, often GIS do not comprehend information that is important for the visually impaired for orientation, such as sidewalks or sonified traffic lights (Kammoun, Dramas, Oriola, & Jouffrais, 2010).

Some critiques concern the representation of map content. First, because of the perceptual limits of the tactile sense, less detail can be represented on a tactile map than on a visual map. Once the map is printed, its content is static and cannot be adapted dynamically. Therefore these maps are quickly out of date (Yatani, Banovic, & Truong, 2012). It is also difficult for visually impaired people to access specific information such as distances. Whereas maps for sighted people normally present a scale in order to indicate distances, this is more difficult on maps for the sight impaired. Furthermore, as discussed above the use of braille labels is problematic.

This leads to the question how new technology can improve access to spatial information for visually impaired people.

II.3.4 From Paper to Interactive Maps

While maps have traditionally been hard copy maps, the rise of new technologies provides new possibilities. Interactive and multimodal maps now exist on computers and smart phones. Schöning (2010b) presented a variety of interactive maps for sighted people on different devices with varying display size. Other interactive maps are freely available on the internet, such as for instance Google Maps[6] or Bing Maps[7].

Advantages of interactive maps in contrast to printed maps are new dynamic functionalities such as scrolling and zooming. Search functionality avoids long search times (Oviatt, 1997). Map content can be updated dynamically. In addition, the user can also contribute to the map by editing the content. For instance, in Google Maps users can contribute reviews to points of interest. Moreover, in OpenStreetMap[8]—a free and collaborative Geographic Information System—the content is directly edited by users. Interactive maps can also be based on tangible interaction (Ebert, Weber, Cernea, & Petsch, 2013). Although the analysis of interactive maps for sighted people is interesting, in this thesis we had to focus our research on accessible interactive maps.

[6] https://maps.google.com [last accessed August 13th 2013]

[7] http://www.bing.com/maps/ [last accessed August 13th 2013]

[8] http://www.openstreetmap.org [last accessed August 13th 2013]

II.4 Non-Visual Interaction for Interactive Maps

As argued by Oviatt (1997), interactive maps have the potential to provide a broad spectrum of the population with spatial knowledge, irrespective of age, impairment, skill level, or other factors. To this regard, they might be an interesting means for providing visually impaired people with access to geospatial information. The literature reveals that numerous research projects have been devoted to the design of interactive maps for visually impaired people since 1988. The design of these maps varied in different aspects, including content, devices and interaction techniques. In this thesis we were interested in understanding the design space for non-visual interactive maps (Research Question 1: What is the design space for interactive maps for visually impaired people?). Concretely we wanted to understand which design possibilities have been developed in earlier projects. We were also interested in experimental results with the different prototypes.

For the purpose of understanding the design space, we produced a classification of research projects on accessible interactive maps. Our survey revealed that there has been little research effort on structuring this area of knowledge. Zeng and Weber (2011) classified interactive maps for visually impaired people depending on the devices that were used in the prototype: audio output alone; haptic devices such as force feedback mice, optionally combined with auditory output; printed raised-line maps, touchscreen and auditory output; and finally novel displays with pins that raise and thereby deform the surface. They analyzed each map type regarding material, map size, amount of information, representation of information, production method and interaction techniques. Even though their classification is an interesting basis for structuring interactive map research, it lacks completeness as only a part of all existing map projects has been analyzed. Furthermore, we believe that it is possible to differentiate the interactive maps regarding more detailed criteria, for instance non-visual interaction techniques. More recently, Kaklanis, Votis, and Tzovaras (2013) presented an overview of different accessible interactive prototypes. Their classification analyzed prototypes regarding the type of information being explored, target user groups, interaction modalities, devices and experimental results. This classification contained map prototypes but was not limited to this. For instance, they also analyzed line graph prototypes. We proposed a classification of interactive maps for visually impaired people in a prior publication (Brock, Oriola, Truillet, Jouffrais, & Picard, 2013). In this thesis we present an extended version of the previous classification.

To this purpose, we performed an exhaustive search with the aim of covering as many relevant publications as possible. A search through scientific databases (ACM

Digital Library, SpringerLink, IEEE Explorer, and Google Scholar) revealed 43 articles that were published over the past 26 years that matched our inclusion criteria. First, we only considered interactive maps that aimed at visually impaired people. Second, we searched for publication in a journal or peer-reviewed conference. Projects that have been published as PhD Thesis or Master Thesis only have not been considered. Third, publications that proposed concepts without implementation were also discarded, except for Parkes (1988) who presented the very first prototype. Fourth, we only considered one publication for each prototype. Exceptions were made if changes occurred between versions of different prototypes. For instance, Weir, Sizemore, Henderson, Chakraborty, and Lazar (2012) based their prototype on the one proposed by Zhao et al. (2008) but changed the content of the map. Pielot, Henze, Heuten, and Boll (2007) based their map on a prior prototype (Heuten, Henze, & Boll, 2007) but integrated tangible interaction. Kaklanis et al. (2013) integrated speech output in their second prototype, whereas their first prototype (Kaklanis, Votis, Moschonas, & Tzovaras, 2011) was based on non-speech output. Fifth, we focused on interactive maps and not on guidance systems. Therefore, we also excluded systems that presented map information purely from an egocentric perspective. This concerned virtual environments that commonly present environments from a egocentric perspective as the user can walk around and perceive the environment from a traveler's perspective (see for instance Kammoun, Macé, Oriola, & Jouffrais, 2012; Lahav & Mioduser, 2008; Merabet, Connors, Halko, & Sánchez, 2012). Some projects on the transition between egocentric and allocentric perspective were included in our overview. For instance, Hamid and Edwards (2013) presented a map from a bird's eye view. Yet, this map could be turned in order to follow the egocentric perspective of the observer. The prototype presented by Pielot et al. (2007) was based on 3D sound that adapted to the rotation of a tangible object. Yet, the object itself was situated in an allocentric reference frame. Milne, Antle, and Riecke (2011) provided 3D sound that adapted to the user's body rotation. However, their prototype also worked with a tangible object on a touch interface, thus in an allocentric reference frame. The prototype of Heuten et al. (2007) was included in our classification but not the one of Heuten et al. (2006). The prototype of Heuten et al. (2007) was an extension of the earlier prototype including a bird's eye view perspective. When it comes to user studies some additional publications have been considered, that have been conducted with the prototypes in the original corpus.

Note that some prototypes allowed different variations. For instance, Parente and Bishop (2003) proposed a system that works with different input devices. Other projects allowed to display more than one type of map content (e.g., Schmitz & Ertl, 2012). In these cases our analysis takes into account all variations. Due to this reason, the number of map prototypes for each classification criteria is not necessary equal to 43. It is also important to underline that in some cases the publications did not give clear information about certain aspects. For instance, sometimes a map prototype is presented without specifying which kind of content is displayed on the map.

In the following subsections we will only detail the analysis of this map corpus regarding non-visual interaction. In the appendix (VII.5) we provide an additional analysis of the corpus with regard to terminology, origin of the map projects, timeline and map content and scale. We also present projects that have been developed outside academia (VII.5.5).

II.4.1 Modalities in Interactive Maps for Visually Impaired People

We analyzed the corpus of interactive map projects for visually impaired people regarding modalities. The analysis was based on definitions of devices, modalities, interaction techniques and multimodality as can be found in the appendix (VII.1).

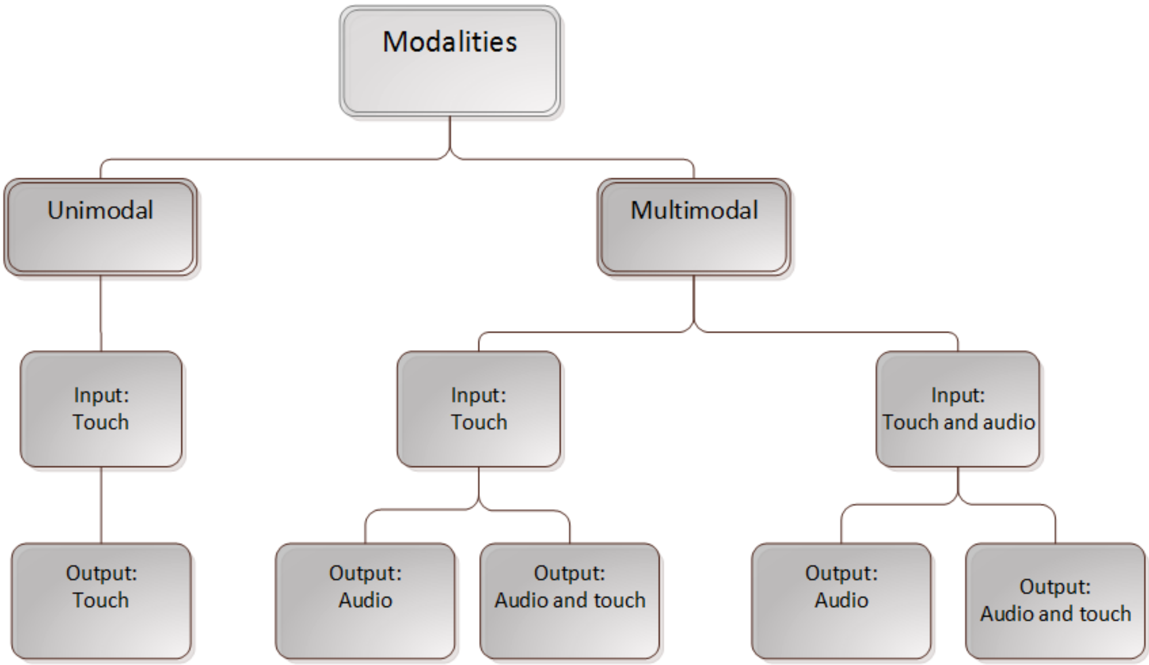


Figure II.9: Overview of modalities employed in the interactive map prototypes for visually impaired people.

Figure II.9 shows how modalities have been used in existing interactive map prototypes. We distinguished modalities that relate to the two senses audition and touch (including cutaneous, kinesthetic and haptic perception). Most systems relied on some sort of touch input and only few systems used both touch and audio (speech recognition) as input (Bahram, 2013; Iglesias et al., 2004; Kane, Morris, et al., 2011; Kane, Frey, & Wobbrock, 2013; Simonnet, Jacobson, Vieilledent, & Tisseau, 2009). In these prototypes audio and touch input were assigned to different tasks. Only the system by Bahram (2013) provided redundant input interaction. Touch and speech input are presented in detail in subsection II.4.3. When looking at the output modalities, all systems relied on some form of audio output except the prototype proposed by Levesque et al. (2012). Some prototypes combine audio output with some form of touch output. Audio and touch output are presented in detail in subsection II.4.4.

According to Bernsen (2008) a unimodal interactive system is a system which uses the same single modality for input and output. In the corpus of interactive maps, only one map prototype was unimodal as it relied on the sense of touch both as input and as output (Lévesque et al., 2012). The aim of this study specifically was to compare conditions of tactile representation of maps. All other prototypes that we have studied used at least two different modalities for input and/or output and were thus multimodal system. Multimodality appears interesting in that the combination of two or more modalities allows to overcome the expressive weaknesses of each of the modalities individually (Bernsen, 2008). Indeed, several studies have demonstrated an advantage for multimodal systems. In a study by Golledge et al. (2005), users had to identify shapes either with a haptic mouse alone or with a haptic mouse and additional auditory cues. Identification accuracy was higher in the multimodal than in the unimodal condition. Oviatt (1996) observed sighted users exploring interactive maps with either unimodal (speech input) or multimodal input. Her study revealed higher performance errors, more disfluencies and longer task completion time for the unimodal than for the multimodal condition. Users also preferred the multimodal map. Crossan and Brewster (2008) studied the teaching of shapes and gestures to visually impaired people either with unimodal haptic output or with complementary haptic and audio output. Their study revealed that participants performed significantly better when presented with multimodal output than with haptic output alone, both concerning recognition and reproduction of shapes. Few studies within the corpus of interactive maps compared the effect of unimodal and multimodal design on usability. Yatani et al. (2012) compared the externalized mental maps of twelve visually impaired users after using either a map with audio output, or a map with complementary audio and vibro-tactile output. When users were asked to model their cognitive maps, the result was more accurate in the multimodal than in the audio condition. Furthermore, participants reported that the vibro-tactile feedback improved their memory for spatial relations. Concretely, they stated that the purely auditory feedback led to an overload of information and that it was quicker and easier to integrate information from both channels. Likewise, Lazar et al. (2013) reported that usability of their prototype was increased by a multimodal approach, in particular by using a touchscreen with auditory output and a tactile map overlay. These findings support the hypothesis that multimodal combination of modalities can overcome weaknesses of each single modality (Bernsen, 2008).

II.4.2 Devices

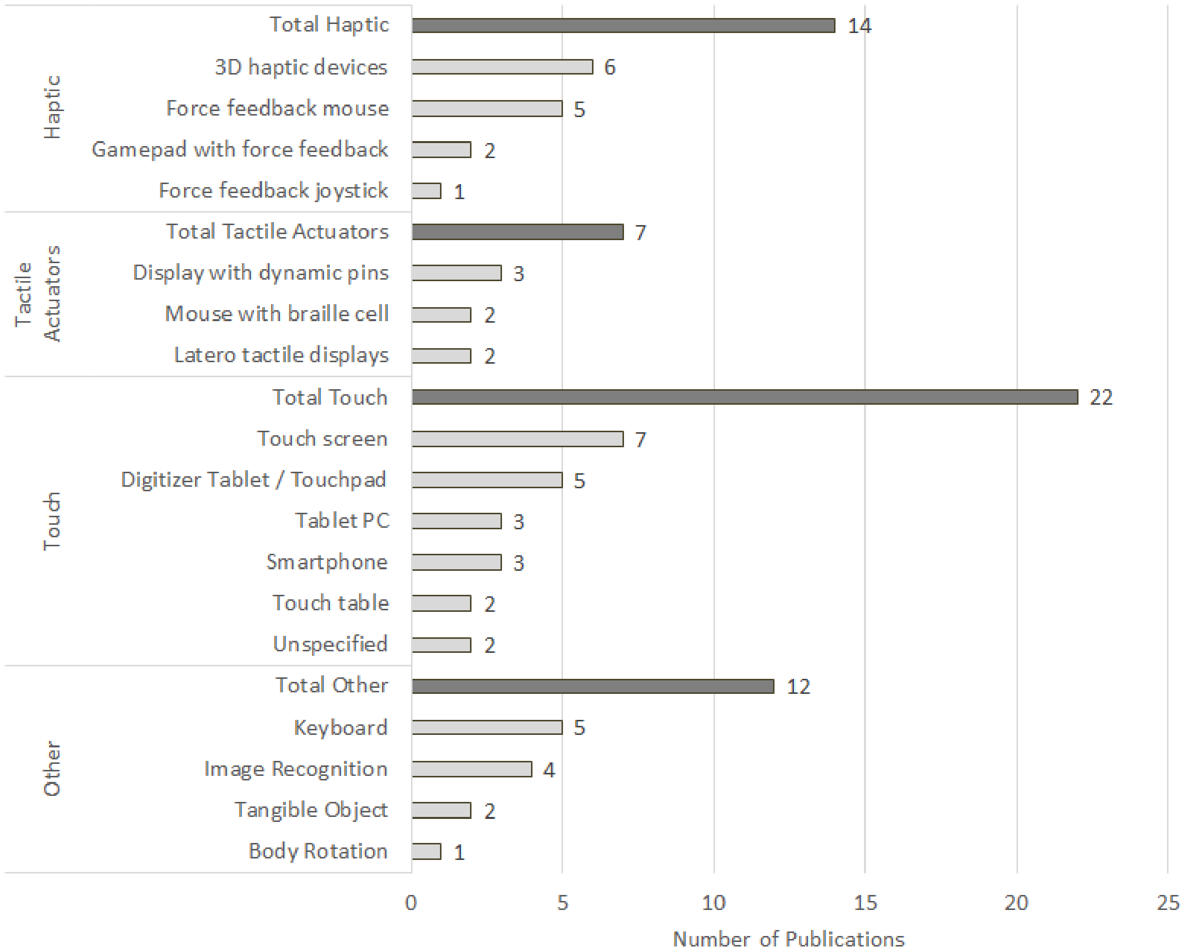


Figure II.10: Number of publications on interactive maps for visually impaired people classified by devices. Categories are presented on the left grouped by the main categories Haptic, Tactile actuators, Touch and Other. The x-axis represents the number of publications. Bars in dark grey present the total for each category.

It is important to analyze the use of different devices as the user has the most direct contact with the system's hardware. Also it has been shown that the type of device contributes to the mental representation that the user creates through interaction (Buxton, 1986). Additionally, different devices are adapted for the execution of different tasks. Devices are not identical to interaction techniques, but interaction techniques are closely linked with the devices. An interaction technique is a way of using a physical device to perform a task in human-computer interaction (Foley, Van Dam, Feiner, & Hughes, 1996). More precisely, interaction techniques are defined by the combination of a physical device and an interaction language (Nigay & Coutaz, 1997). In the case of interactive maps we judged it more interesting to look at devices that react to or produce haptic output, as there is a larger variety in haptic than in audio devices (i.e., headphones and loudspeakers produce the same audio information). We will have a closer look at the audio input in subsection II.4.3.1 and audio output in subsection II.4.4.1.

It is also possible to distinguish between input and output devices. Input devices are controlled by the user to communicate information towards the computer (Dragicevic, 2004). Output devices present information from the system to the user. Some of the devices in our classification sense input, some also actively provide output. For instance, haptic devices react to the user input, but do also apply a force in order to render kinesthetic cues to the user. We propose to classify the devices in four categories according to common principles of sensing input and representation of information: haptic devices, tactile actuator devices, touch-sensitive devices and other (Figure II.10).

II.4.2.1 Haptic Devices

With the term "haptic devices" we describe devices which execute force feedback. This means that they mechanically produce a force that is perceived as a kinesthetic sensation by the user who is touching the device (El Saddik, Orozco, Eid, & Cha, 2011). Hence haptic devices include sensors and actuators, and serve as input and output devices. We further distinguished different haptic devices.

Figure II.11: Photograph of the GRAB interface as presented by (Iglesias et al., 2004). Reprinted with permission.

First there are devices that allow interacting in three dimensions through a handle such as the Geomagic Touch X[9] (formerly the Sensable Phantom Desktop) or the Novint Falcon[10]. Both are tensioned cable systems, i.e. the handle is moved to different directions by several actuated cables (El Saddik et al., 2011). The resulting force is perceived by the user grasping the handle. These devices allow a large workspace. The

[9] http://geomagic.com/en/products/phantom-desktop/overview [last accessed August 21st 2013]

[10] http://www.novint.com/index.php/novintfalcon [last accessed August 21st 2013]

Geomagic Touch X provides six degrees of freedom (DoF), i.e. the possibility to vary position and orientation along the three spatial axes, as well as 3D force feedback. The Novint Falcon allows three DoF (El Saddik et al., 2011). Several maps have been implemented with these devices (De Felice, Renna, Attolico, & Distante, 2007; Kaklanis et al., 2011, 2013; Lohmann & Habel, 2012; Simonnet et al., 2009). Iglesias et al. (2004) worked with the "GRAB" interface (see Figure II.11). This device also uses 3D force-feedback. It was based on two distinct robotic arms placed on two bases in front of a visualization screen. Both robotic arms possessed six DoF and covered a workspace of 0.6 m width, 0.4 m height and 0.4 m depth. Two fingers, either of the same or two hands, could be placed in two thimbles to which two independent force-feedbacks were applied.

Computer mice with force feedback have been used in some projects (Campin, McCurdy, Brunet, & Siekierska, 2003; Lawrence, Martinelli, & Nehmer, 2009; Parente & Bishop, 2003; Rice et al., 2005; Tornil & Baptiste-Jessel, 2004). Force feedback mice function as standard computer mice with the additional capability to produce programmable haptic sensations (Rice et al., 2005).

Alternatively, gamepads with force feedback have been proposed (Parente & Bishop, 2003; Schmitz & Ertl, 2010) as well as force feedback joysticks (Parente & Bishop, 2003). Both are affordable and widely employed. They generally possess a small number of DoF and moderate output forces (El Saddik et al., 2011).

II.4.2.2 Tactile Actuator Devices

We defined tactile actuator devices as devices that sense user input and dynamically execute a cutaneous stimulation on the user's skin. It corresponds to the term "tactile interfaces" used by El Saddik et al. (2011). Tactile actuator devices can mimic tactile sensations such as pressure, texture, puncture, thermal properties or friction (El Saddik et al., 2011). Hence they reproduce local features of objects such as shape and relief.

Many devices use mechanical needles or pins that are raised mechanically either by electromagnetic technologies, piezoelectric crystals, shape memory alloys, pneumatic systems or heat pump systems (El Saddik et al., 2011). Visually impaired people commonly know this kind of stimulation, as they often use dynamic braille displays that are based on a similar principle (Brewster & Brown, 2004). These braille displays are used for displaying textual information (see Figure II.12). Braille displays are made of a line of 40 to 80 cells, each with 6 or 8 movable pins that represent the dots of a braille letter (Brewster & Brown, 2004). The user can read a line of braille text by touching the raised pins of each cell. As presented by Borodin, Bigham, Dausch, and Ramakrishnan (2010) braille displays are an interesting alternative to audio output. They present the same information as audio output in an alternative modality, making information less fugacious. In contrast to audio output, braille displays give users the possibility to spend as much time as they want on reading the content and repeat reading if necessary. Additionally, spelling of words can be made accessible to visually impaired people. Although this has also been done with speech output (Miele, Landau, & Gilden, 2006), presenting the spelling of words seems easier when written than when spoken. Finally, the ISO standard 16071 suggests to enable output alternatives in different modalities (ISO, 2003), so it appears advantageous to provide audio as well as braille output. The disadvantage of braille displays consists in their elevated price. Despite the above reported advantages, within the corpus of interactive map projects, a braille display has been used in only one prototype for displaying textual information (Schmitz & Ertl, 2012). As it has only been used as a complement and not for displaying spatial information we have not mentioned it in Figure II.10.

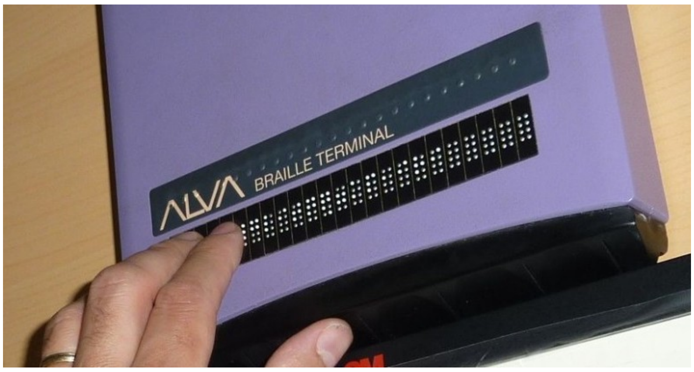
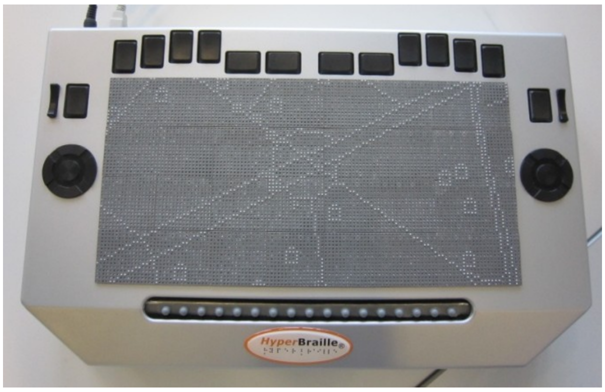


Figure II.12: A blind person reading text on a dynamic Braille display.

So far, few alternative tactual actuator systems are commercially available. Within the corpus of interactive maps, several prototypes use displays of various size composed by actuated pins (Schmitz & Ertl, 2012; Shimada et al., 2010; Zeng & Weber, 2010). These displays function as a tactile map: the information is displayed as relief and the user moves the hand across the display for exploring. In addition, it is possible to dynamically change the content or to highlight elements by dynamically altering raised and recessed pins. Concretely, Zeng & Weber (2010) used the BrailleDis 9000 tablet which was composed by 7200 pins actuated by piezo-electric actuators and arranged in a 60x120 pin matrix (see Figure II.13 a). Schmitz & Ertl (2012) used the HyperBraille display[11], a commercial version of the BrailleDis 9000. Shimada et al. (2010) constructed a display with 3072 raised pins. This system additionally had a scroll bar that showed which parts of

[11] http://www.hyperbraille.de/?lang=en [last accessed August 21st 2013]

the image were outside the displayed area. Both devices contained touch sensors in order to react to user input.



(a)

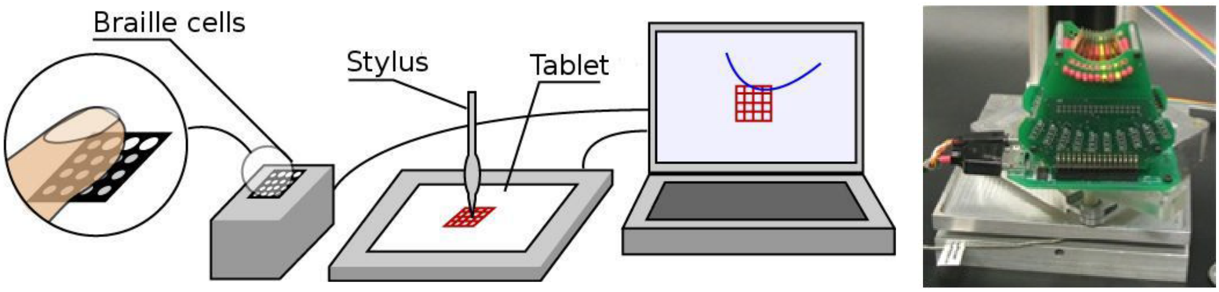
(b)

Figure II.13: Tactile actuator devices. (a) BrailleDis 9000 tablet as used by (Zeng & Weber, 2010). (b) VTPlayer mouse with two 4x4 arrays of pins. Reprinted with permission.

The production of raised-line displays is expensive, and obviously smaller raised-pin displays have lower costs than the larger ones (Pietrzak, Crossan, Brewster, Martin, & Pecci, 2009). In comparison with large displays, mice with braille cells have a small display approximately in the size of one or two braille characters. For instance the VTPlayer by VirTouch is a tactile mouse that has two 4x4 arrays of pins. These arrays are destined to rest under the index and middle finger while the user moves the mouse (Figure II.13 b). The information on the display changes in relation with the moving mouse position (Jansson, Juhasz, & Cammilton, 2006). Tixier et al. (2013) proposed Tactos, a system with two fixed braille cells and a separate pointing device (see Figure II.14 a). Moving the pointing device determined which information was displayed on the braille cells. The pointing device could be of different types, for instance a digitizer tablet. This device was not a mouse as the movement device and the device with the cutaneous feedback are separated. However, in order to reduce complexity of the diagram we have classified it as such in Figure II.10.

In the laterotactile system proposed by Petit et al. (2008), tactile feedback was produced by laterally stretching the skin of the finger (Figure II.14 b). This was done by two assembled devices: the "$STReSS^2$" (Stimulator of Tactile Receptors by Skin Stretch) and the "Pantograph". The $STReSS^2$ device contained a matrix of 8x8 piezoelectric bending motors that moved laterally by approximately 0.1 mm and produced a force of around 0.15 N (Lévesque & Hayward, 2008). The size of the tactile feedback zone was 12x10.8 mm. The Pantograph allowed movements on a two-dimensional surface. The $STReSS^2$ mounted on the Pantograph then related tactile feedback to the position on the

2D surface. A revised but functionally equivalent display was used by Lévesque et al. (2012).



(a) (b)

Figure II.14: Tactile actuator devices. (a) Schema of the Tactos device as proposed by (Tixier et al., 2013) (b) The STReSS2 laterotactile device as used by (Petit et al., 2008)**. Reprinted with permission.**

II.4.2.3 Touch-Sensitive Devices

Many prototypes are based on touch-sensitive surfaces. With the term touch-sensitive devices we regroup different technologies that directly sense the user's touch input. Some of these devices are mono-touch, whereas others are multi-touch (see III.2.3.3 for an analysis of different multi-touch technologies). Some react to bare fingers, whereas others require a pen for input. Touch-sensitive surfaces do not actively provide feedback. They are thus pure input devices and are usually associated with visual feedback. Therefore, most touch-sensitive devices remain inaccessible to visually impaired people. Yet, indirectly feedback is provided through the cutaneous sensation at the fingertip and the kinesthetic sensation of the exploratory hand movements within a fixed haptic reference frame (see II.4.4.2). In many accessible map prototypes, the touch-sensitive surface is combined with raised-line map overlays (Figure II.19) or with vibro-tactile stimulation in order to add tactile information.

Within the corpus, most touch-sensitive maps were based on touch screens, i.e. static touch-sensitive devices having the size of a regular computer screen (Brock, Truillet, Oriola, Picard, & Jouffrais, 2012; Campin et al., 2003; Hamid & Edwards, 2013; Miele et al., 2006; Senette, Buzzi, Buzzi, Leporini, & Martusciello, 2013; Wang, Li, Hedgpeth, & Haven, 2009; Weir et al., 2012). Some prototypes were based on touchpads or digitizer tablets (Daunys & Lauruska, 2009; Heuten et al., 2007; Jacobson, 1998a; Parente & Bishop, 2003; Zhao et al., 2008). These tablets have been commercially available before multi-touch surfaces. Recently, tablet PCs (Carroll, Chakraborty, & Lazar, 2013; Senette et al., 2013; Simonnet, Bothorel, Maximiano, & Thepaut, 2012) and smartphones (Poppinga, Magnusson, Pielot, & Rassmus-Gröhn, 2011; Su, Rosenzweig, Goel, de Lara, & Truong, 2010; Yatani et al., 2012) have been used. These devices allow using an interactive map in mobile situations. Few prototypes were destined for touch tables, i.e. large touch-sensitive surfaces (Kane, Morris, et al., 2011; Yairi, Takano, Shino, & Kamata, 2008). Finally, some projects did not specify the type or size of touch device and might therefore function with different hardware (Bahram, 2013; Parkes, 1988).

II.4.2.4 Other Devices

A last category regrouped all devices with different technology. First, some prototypes integrate keyboard use (Bahram, 2013; Parente & Bishop, 2003; Simonnet et al., 2009; Weir et al., 2012; Zhao et al., 2008). In some cases, a keyboard was provided as supplementary input device, for instance for entering textual information. Some prototypes were based on image recognition (Kane, Frey, et al., 2013; Krueger & Gilden, 1997; Schneider & Strothotte, 1999; Seisenbacher, Mayer, Panek, & Zagler, 2005). A camera is filming the map and user's hands. The image was then analyzed to localize the hand touching the map (see Figure II.15). The user thus interacts with the map as if it was based on a touch-sensitive surface. Few projects investigated tangible interaction for non-visual interactive maps, i.e. interaction through physical objects (Milne et al., 2011; Pielot et al., 2007). Finally, Milne et al. combined the use of tangible interaction with the rotation of the user's own body.

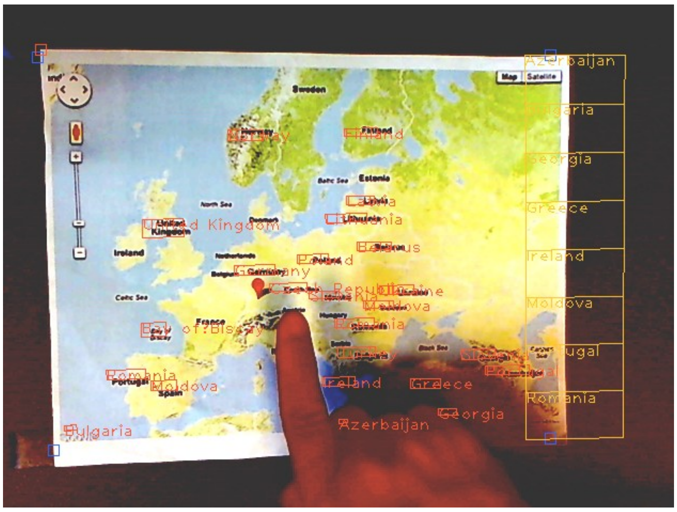


Figure II.15: Access Lens application as proposed by (Kane, Frey, et al., 2013). The map labels are located and recognized by image recognition and then translated into speech output. The menu on the right displays an index of on-screen items. Reprinted with permission.

II.4.2.5 Summary

To sum up, from Figure II.10 it is obvious that a lot of prototypes are based on touch-sensitive devices. This is certainly favored by recent technical advancements, which have led to very affordable touch devices. Haptic devices, as the Phantom, are usually more expensive. Displays with tactile actuators appear very interesting, as they provide refreshable cutaneous information. However, many of the projects are not yet commercialized or are very expensive. For instance, in 2012 the HyperBraille terminal cost about 50 000€. The use of tangible interaction has been very little studied and it might be interesting to further investigate this possibility. Few studies have compared the use of different devices. Lazar et al. (2013) observed five blind users exploring a map either with a keyboard, a touchscreen interface or a touchscreen with raised-line overlay. Their study showed that users preferred the touchscreen with overlay over the touchscreen alone and the keyboard interface. We therefore conclude that touch-sensitive devices appear to be affordable and interesting solutions.

II.4.3 Input Interaction

Input interaction techniques used in interactive maps rely either on the use of audio or touch. In a study where users were given the choice between touch and speech input they chose input modalities based on the type of task (Chen & Tremaine, 2005). They primarily used touch input for navigation tasks, and speech input for other tasks. It is therefore interesting to analyze how different interaction techniques have been used in interactive map prototypes. Audio, in the form of speech recognition, is often used with a complementary function to touch input in interactive map prototypes. Most of the input in interactive map prototypes is done via touch. Indeed whether users use keyboard, computer mouse, haptic device or touchscreen, touch is always involved. The following subsections pinpoint interaction techniques that have been used in the corpus of interactive maps.

II.4.3.1 Speech Recognition

Speech recognition is the audio input interaction that can be found in interactive map prototypes. The interest of speech input over other input modalities is that eyes and hands can be busy, as is often the case in mobile situations (Oviatt, 1997). This input technology is adapted for people with special needs, including people with visual and motor impairments. Speech recognition is also a more natural way of interacting than for instance typing on a keyboard (Feng & Sears, 2009). In addition, it allows a higher input bandwidth than typing with up to 200 words per minute (Bellik, 1995).

On the other hand, the adoption rate for speech input systems is low and users often report many problems. It has been observed that actual recognition rates of these systems are often lower than those indicated by suppliers (Feng & Sears, 2009). In addition confidentiality is problematic, as speech input is public (Bellik, 1995). It is also subject to interference with the environment as the system needs to distinguish between input commands and background noise, or the user speaking to another person (Bellik, 1995). Finally speech input cannot be used in all situations, such as a classroom or a theater.

To reduce recognition problems it is possible to limit the input vocabulary (Feng & Sears, 2009). It is also important to choose an adapted vocabulary. Short words or words that sound similar make it more difficult for the system to recognize the input correctly (Bellik, 1995). Oviatt (1997) suggested to guide users' language toward simplicity. Furthermore, the environment influences the recognition rate, for instance the quality of the microphone or the background noise. Recognition rate can also be improved by training the system to the voice of the interlocutor (Bellik, 1995).

Oviatt (1996) compared interactive maps for sighted people based on speech input with maps based on speech recognition and pen input on a touch surface. She observed that the time for completing map-based tasks was shorter with multimodal than speech input. She argued that it was easier, quicker and more precise to designate locations and shapes by touch than by speech. Also the number of disfluencies was higher in the speech-only condition, due to the difficulty to express spatial locations by speech. On the other hand, speech-input allowed users to locate objects that were not currently displayed on the screen, simply describing landmarks and streets. Speech also allowed a dialogue with the map interface, such as asking for navigational assistance or information about specific landmarks.

Some interactive map projects for visually impaired people used speech input as complementary interaction technique. Whereas position information was acquired through touch input, speech recognition allowed to access additional information, such as distances (Simonnet et al., 2009), directions (Kane, Morris, et al., 2011; Kane, Frey, et al., 2013; Simonnet et al., 2009) or lists of on-screen or nearby targets (Kane, Morris, et al., 2011; Kane, Frey, et al., 2013). Speech recognition was also used for centering the map on a point or for zooming (Bahram, 2013).

II.4.3.2 Touch

As mentioned before, touch is involved in the use of many different devices, such as computer mice, keyboards, touch surfaces or haptic devices.

II.4.3.2.a Standard Devices

Dragicevic (2004) differentiated between standard and non-standard touch input devices. Interestingly, the computer mouse, which is a standard input device for sighted people, is rarely used by visually impaired people. Usually, feedback regarding the mouse movement is visual and thus visually impaired people cannot easily orient their exploratory movements. However, more accessible mice include force-feedback (Campin et al., 2003; Lawrence et al., 2009; Parente & Bishop, 2003; Rice et al., 2005; Tornil & Baptiste-Jessel, 2004) or cutaneous feedback via a braille cell (Jansson et al., 2006). Similarly, laterotactile devices combined a position-sensing device with cutaneous feedback (Lévesque et al., 2012; Petit et al., 2008). These devices provide input and output. The output modalities of these devices are discussed in subsection II.4.4.2.

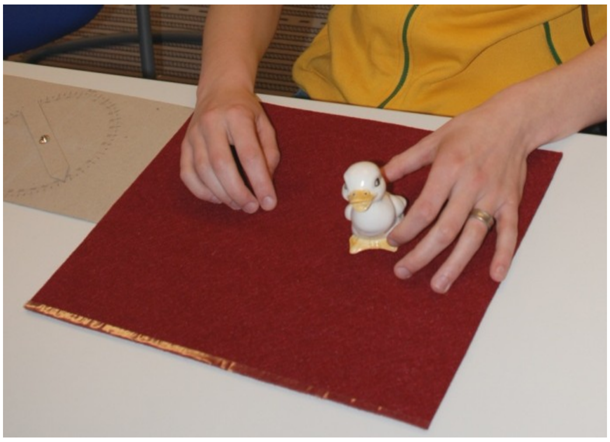
The keyboard is a standard device for both sighted and visually impaired people. It has been used in different interactive map projects (Bahram, 2013; Parente & Bishop, 2003; Simonnet et al., 2009; Weir et al., 2012; Zhao et al., 2008). While typing on a keyboard is very well adapted for entering linguistic information, it appears less adapted to determine locations on a map. Exploring a map by pressing the arrow keys is discrete, symbolic, and less sensitive to irregularities (Delogu et al., 2010). When interacting with a keyboard, the user moves the cursor position on the map step by step with every keystroke, whereas other technologies allow to jump from one point on the map to another (Lazar et al., 2013). In addition keyboard interaction does not provide any reference frame (see II.4.4.2.a). Accordingly, keyboard input is used in some interactive map projects as complementary input rather than for providing the location on the map. For instance, it has been used to change the map heading (Simonnet et al., 2009) or to enter commands such as zooming or scrolling (Bahram, 2013). Delogu et al. (2010) compared navigation in a sonified map with a keyboard or a tablet. Despite the above reported disadvantages of keyboard interaction, they did not observe any significant difference in a map recognition task according to the type of input. Both input interactions led to an effective cognitive map. However, they observed that touch-tablet users explored the map content in more details than keyboard users. Also tablet users changed the direction of exploration more often. Furthermore, they were faster. Delogu et al. suggested that due to the missing haptic reference frame, keyboard interaction demanded more cognitive effort for reconstructing the position after each step.

II.4.3.2.b Haptic Interaction

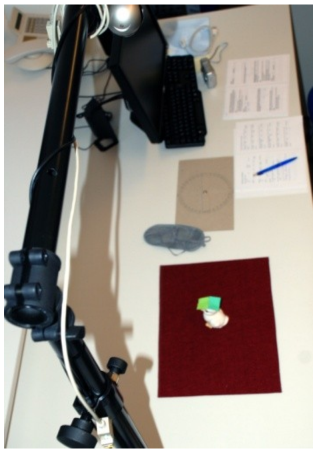
As discussed before, interaction with haptic devices is often done via a single input handle that is moved and eventually rotated in space (De Felice et al., 2007; Kaklanis et al., 2011, 2013; Lohmann & Habel, 2012; Simonnet et al., 2009). An alternative device was based on two handles (Iglesias et al., 2004). As the movements are effected in three dimensions in space, it is hard to keep track of the current position, especially when visual feedback is missing. Despite this difficulty, the various studies within the interactive map corpus have proved that haptic devices can successfully be employed for the exploration of geographic data by visually impaired individuals.

II.4.3.2.c Tangible Interaction

Tangible interaction has been used in interactive map prototypes for visually impaired people (Milne et al., 2011; Pielot et al., 2007). Tangible user interfaces combine physical objects with digital data (Ullmer & Ishii, 2000). Users interact with the system by manipulating one or several physical objects. Users might not necessarily be aware that they are interacting with a computer. For instance (Pielot et al., 2007) used a toy duck as tangible object (see Figure II.16). The user moved the duck on the tangible area (red surface). A camera filming from above kept track of the object's position and orientation and rendered the audio output accordingly. Milne et al. (2011) used a pen-based digitizer tablet with the stylus as tangible object. A button on the stylus indicated the forward direction.



(a)



(b)

Figure II.16: Tangible interaction as proposed by (Pielot et al., 2007). (a) User interacting with the tangible object, a toy duck. (b) The setup: camera filming from above. Reprinted with permission.

In general, few projects have investigated the use of tangible interaction in non-visual contexts. McGookin, Robertson, & Brewster (2010) developed a tangible prototype for the non-visual exploration of graphs. This system combined a fixed grid for orientation and movable tangible objects. User studies with visually impaired people revealed high accuracy both for constructing and exploring graphs. The evaluation allowed providing guidelines for the development of tangible interfaces for visually impaired people. For instance tangible objects should be physically stable so that users do not knock them over while exploring the interface. Although first experiments with non-visual tangible interaction are promising, there is surprisingly little work in this area.

II.4.3.2.a Touch input

A more direct input is based on touch input. Touch input refers to interaction of a finger on a touch-sensitive surface. The position of the finger corresponds to the cursor position on the display, within the reference frame of the surface. Within the interactive map corpus, this has been achieved via different technologies. Large raised-pin displays possess touch sensors (Schmitz & Ertl, 2012; Shimada et al., 2010; Zeng & Weber, 2010). Image recognition can be used to track hand movements (Kane, Frey, et al., 2013; Krueger & Gilden, 1997; Schneider & Strothotte, 1999; Seisenbacher et al., 2005). However, the most common devices for touch input are touch-sensitive surfaces, such as smartphones (Poppinga et al., 2011; Su et al., 2010; Yatani et al., 2012), tablet PCs (Carroll et al., 2013; Senette et al., 2013; Simonnet et al., 2012), digitizer tablets (Daunys & Lauruska, 2009; Heuten et al., 2007; Jacobson, 1998a; Parente & Bishop, 2003; Zhao et al., 2008), touchscreens (Brock, Truillet, et al., 2012; Campin et al., 2003; Hamid & Edwards, 2013; Miele et al., 2006; Senette et al., 2013; Wang et al., 2009; Weir et al., 2012) or touch tables (Kane, Morris, et al., 2011; Yairi et al., 2008). Gestural interaction is a specific type of touch interaction that will be presented in more detail in the following subsection.

Gestural Interaction

The rise of multi-touch devices has led to an increased use of gestural interaction in general. However, gestural interaction has so far rarely been used in interactive maps for visually impaired people. Yet, we believe that this interaction technique is promising. In this subsection we do not investigate how recognition of gestures is technically implemented but how this interaction technique can be used for non-visual exploration of geographic data.

In a first step we investigated how gestural interaction is defined. This is challenging, as no standard definition exists (Kamber, 2011). Gestures are an integral part of human communication in general, and the term is broad and rich (Buxton, 2013). Some definitions have been made in the context of HCI. Pavlovic, Sharma, & Huang (1997) argued that gestures differed from unintentional movements in that they convey meaningful information. They proposed that gestures could either be used to manipulate objects or to communicate information. Dragicevic (2004) defined gestural interaction as an unconventional means of employing pointing devices by exploring the muscular capacities to memorize and reproduce trajectories. He argued that in contrast to pointing devices, which only look at the current position of a pointer, gestural interaction makes use of dynamics. Kamber (2011) summarized definitions of gestural interactions from different authors. He concluded that gestures were movements created by the hand, arm or another part of the body, that these movements followed a certain path or sequence, and that the data was being captured to trigger an event. To sum up, the term gesture defines dynamic and intentional movements of certain body parts (likely the hands and arms). Because these movements follow a defined path they can be recognized by a computer and trigger a reaction.

Some studies focused on the design of usable gestures. Morris, Wobbrock, and Wilson (2010) studied users' preferences for gestures that were either created by three HCI researchers or by end users. They observed that users preferred gestures that have been designed by a greater number of people. Users also preferred simple gestures, for instance gestures using one finger instead of the whole hand, or one handed gestures over two-handed gestures. They noted that researchers alone tended to develop gestures that were too complex. Nacenta, Kamber, Qiang, and Kristensson (2013) studied memorability of user-designed gestures, pre-defined gestures and random gestures. They observed an advantage of user-defined gestures over pre-defined gestures and a significant disadvantage of the random gestures in comparison with the two other conditions. The study also revealed that the difference in memorability often occurred from association errors between the gesture and the resulting action, and not from incorrect execution of the gestures. Both studies can be seen as a strong argument in favor of developing gestural interaction in a participatory design process. Yet, as argued by Nacenta et al. (2013) it is not always possible to imply users in the creation of gesture sets. For instance it is technically more challenging to recognize user-created gestures. Designers pay attention to define gestures that are sufficiently different for the gesture recognizer, whereas for user-designed gestures the differences between two gestures might be very small. Also it may be desired that gestures are the same between different applications, and thus defining specific gestures is not possible.

Accessibility of Touch Displays

Touch displays per se possess a poor accessibility for visually impaired people. As Buxton (2007) stated on the accessibility of multi-touch screens: "If you are blind you are simply out of luck." Buxton criticized several aspects about touch displays. First, there is no tactile feedback. In contrast with a traditional button based interface, when using a touchscreens you cannot feel your way to an interface component. Second, if feedback is given, than it is often about the last effected action, but not about the current position or the next action to take. Third, in some applications the position of interactive elements on the screen is not fixed so the user cannot even memorize the position. This has been confirmed in experiments (Kane, Bigham, & Wobbrock, 2008). Furthermore, visually impaired people stated to be anxious about accidentally activating features on the screen. Finally, they also expressed a preference for familiar layouts.

As touch screens become widely spread, making them more accessible to visually impaired people is an important task. Kane, Morris, et al. (2013) classified touch screen accessibility in three categories. First, there are software only approaches. They make use of accessible gestural interaction and audio output. This category includes commercial solutions as for example proposed by Apple[12]. Second, hardware-only approaches apply hardware modifications on the touchscreen. For instance, some visually impaired people glue tactile dots and braille labels on the screen (Kane et al., 2008; S. Xu & Bailey, 2013). Third, hybrid approaches combine the use of hardware modifications, such as overlays, and audio output. Audio-tactile maps (interactive maps that are based on raised-line overlays and speech output) are for instances included in this category.

McGookin, Brewster, and Jiang (2008) compared a hybrid to a software based approach. Concretely, they studied two different MP3 players for visually impaired people, one based on a touchscreen with a raised-line overlay, the other one based on a touchscreen with gestural interaction and without overlay. Both prototypes had audio feedback. In a study with 12 blindfolded participants, McGookin et al. observed that in the overlay condition, performance was significantly faster and participants did fewer errors. Also, participants expressed a preference for the overlay. Problems with the gestural prototype included longer learning time for the interaction techniques as well as accidental touch input. The button overlay on the other hand demanded additional preparation time. In a qualitative study with one blind user, the user found it difficult to keep track of his relative position on the screen. Furthermore, when the user wanted to gain an overview of the application he accidentally activated interaction. This study led to a set of guidelines for accessible gestures. First, McGookin et al. proposed not to use short impact related gestures such as simple taps as this led to unintended touch events. Second, they suggested to avoid localized gestures or to provide a reference system. Third, feedback should be provided for all actions.

Accessibility of Gestural Interaction

In the following we will concentrate on "software only" accessibility projects, specifically on accessible gestural interaction. The advantage of software based approaches in comparison with hardware-based and hybrid approaches is that they are often less costly than adapting the hardware. To this end, Slide Rule provided a set of accessible gestures for touch screen interfaces (Kane et al., 2008). Design principles of Slide Rules were to provide screen exploration without the risk of accidentally executing an action, to provide a resolution that was adapted for the finger and not for the eye, to

[12] http://www.apple.com/accessibility/ios/ [last accessed September 16th 2013]

reduce the demand for selection accuracy, to provide quick browsing and navigation, to make gestural mapping intuitive and to enable a "return home" function. Basic interaction techniques that have been developed as a result of this were for instance a one-finger scan for browsing lists, a second finger to tap and select items, a multi-directional flick for additional actions and a L-shaped gesture for browsing hierarchical information. Slide Rule did not have any visual interface but was accessible entirely through gestural input and audio output. Applications that have been made accessible with these gestures included a phone book, an email client and a media player. In a user study with ten blind participants comparing Slide Rule with a Pocket PC device, Slide Rule proved to be significantly faster. However, users made more errors with the Slide Rule prototype. Results concerning satisfaction were contradictory.

Kane, Wobbrock, and Ladner (2011) conducted two user studies on the use of gestural interaction by blind and sighted people. This work was set in the continuity of above reported studies with sighted people that revealed users' preferences for gestures that have been developed by end-users (Morris et al., 2010). In a first study, Kane et al. (2011) asked ten blind and ten sighted users to invent gestures for specific tasks on a tablet PC. Gestures created by blind people varied from those created by sighted people in that blind people showed strong preferences for gestures that included screen corners, edges and the use of multiple fingers. Also, blind participants often proposed gestures based on a QWERTY keyboard layout. In a second study with the same participants, Kane et al. (2011) investigated whether blind and sighted users performed the same gestures differently. This study revealed that gestures produced by blind people were larger, slower and varied more in size than those produced by sighted people. Moreover, they identified that location accuracy, form closure and line steadiness were less precise for blind people. Furthermore, some blind participants were not able to produce gestures, such as letters, numbers and symbols. This led to the establishment of several guidelines for creating gestures for visually impaired people. First, symbols and letters from print writing should be avoided. Second, edges and corners are helpful cues for identifying one's position on the screen and gestures should thus be positioned close to them. Third, the expected location accuracy should be low. This is in line with the guidelines proposed by McGookin et al. (2008). Fourth, gestures should take into account that blind people may need more time for executing them. Finally, it can be useful to rely on familiar layouts such as QWERTY keyboards.

Wolf, Dicke, and Grasset (2011) studied gestural interaction for spatial auditory interfaces on smartphones. Although they did not specifically aim at visually impaired people, the study is interesting because it included not only 2D gestures but also 3D gestures perceived by the inbuilt sensors (e.g. accelerometer or gyroscope). 10 participants have been asked to create gestures for WIMP interface tasks. Most of the created gestures were created on the touch screen, many gestures were based on 3D movements of the phone and only few gestures combined both. Wolf et al. noticed a preference for 2D and 3D gesture combinations with rising task complexity. To our knowledge no study has investigated the use of 3D gestures for visually impaired people.

A different aspect that was evoked in the study by McGookin et al. (2008) was how to teach gestures to blind people. Schmidt and Weber (2009) suggested three methods for this purpose: keeping gestures simple enough to describe them verbally, letting a second person guide the user's hand, or providing illustrations for each gesture. As these methods are not necessarily applicable outside laboratory settings, Schmidt and Weber proposed a technical system for teaching gestures to visually impaired people. This system was based on the previously mentioned BrailleDis 9000 (see II.4.2). The device was capable of detecting a hand positioned on the surface and even to identify fingers and the size of the hand. Gestures were rendered as static or animated relief patterns through the dynamic pins of the display. Although this concept is interesting, it is limited because most blind people do not have access to a raised-pin display. It would therefore be interesting to develop teaching methods for gestures on multi-touch surfaces.

As stated above, gestural interaction is not yet widely spread among interactive maps for visually impaired people. Zeng and Weber (2010) implemented basic gestures such as panning and zoom. Yatani et al. (2012) proposed the use of flick gestures for navigating lists or selecting items. Carroll et al. (2013) suggested using basic gestures such as pinch-to-zoom or drag but altering the action that resulted from the defined movement. Performing a two-finger pinch would then not result in zooming the map but for instance in changing the content. A major contribution has been made by Kane, Morris, et al. (2011) who proposed three innovative types of gestural interaction for large touch table maps. They called these accessible interaction techniques "Access Overlays" because they were technically implemented as transparent windows over an existing map application. In a first bimanual technique, called "Edge Projection", a menu was projected to the edges of the screen. The positions of the points on the map were projected to the x- and y-axis in the edge menu. Users could thus quickly browse the menu for exploring all onscreen targets. If they identified a target they could drag both fingers from the edge to the interior of the screen to locate the desired landmark (see Figure II.17). The second technique was called "Neighborhood Browsing". Its principle was to increase the target size by claiming the empty area around landmarks. Touching within the neighborhood announced the targets name. The system then guided the user to the nearest onscreen target by announcing spoken directions. The third interaction technique was called "Touch-and-Speak". This interaction combined touching the screen with speech recognition, for instance for listing all on-screen targets. Again, it then guided the user to the target by giving spoken directions. 14 blind users compared these three interaction techniques to a standard implementation of Apple's VoiceOver. The results revealed that Touch-and-Speak was the fasted technique followed by Edge Projection. Furthermore, there were significantly more incorrect answers with VoiceOver than with the other techniques. Moreover, users also ranked Edge Projection and Touch-and-Speak significantly better than VoiceOver. Consequently in a later prototype, "Access Lens", Kane, Frey, et al. (2013) implemented an edge menu similar to the one provided in Access Overlays.

Figure II.17: Access Overlays as presented by (Kane, Morris, et al., 2011). The image shows the edge projection technique. The user is exploring the menu on the x- and y-axis. Reprinted with permission.

Touch-screens are today widely employed and it is important to make them accessible. Due to the above reported promising results in making gestural interaction accessible, we believe that gestural interaction is an adapted means for making touch-sensitive devices accessible. We therefore claim that it should be further investigated especially for the development of future interactive map prototypes

II.4.3.3 Summary

In this subsection we presented different input interaction techniques that have been used in interactive maps for visually impaired people. Speech recognition seems promising for accessing complementary information or for entering input commands. However, it seems less well adapted for localizing positions on a map. Different interaction techniques involve the sense of touch. Touch input on a touch-sensitive device appears to be especially adapted for exploring geographic maps. It allows a quicker and more dynamic exploration than for instance keyboard input. The accessibility of touchscreens per se is limited, but can be improved through software, hardware or hybrid solutions. We suggest that accessible gestural interaction should be further investigated. Also, tangible interaction, although rarely used, may provide interesting possibilities.

II.4.4 Output Interaction

As for input, the map output modalities used for visually impaired people are audio and touch. The following subsections precise interaction techniques for both output modalities.

II.4.4.1 Audio

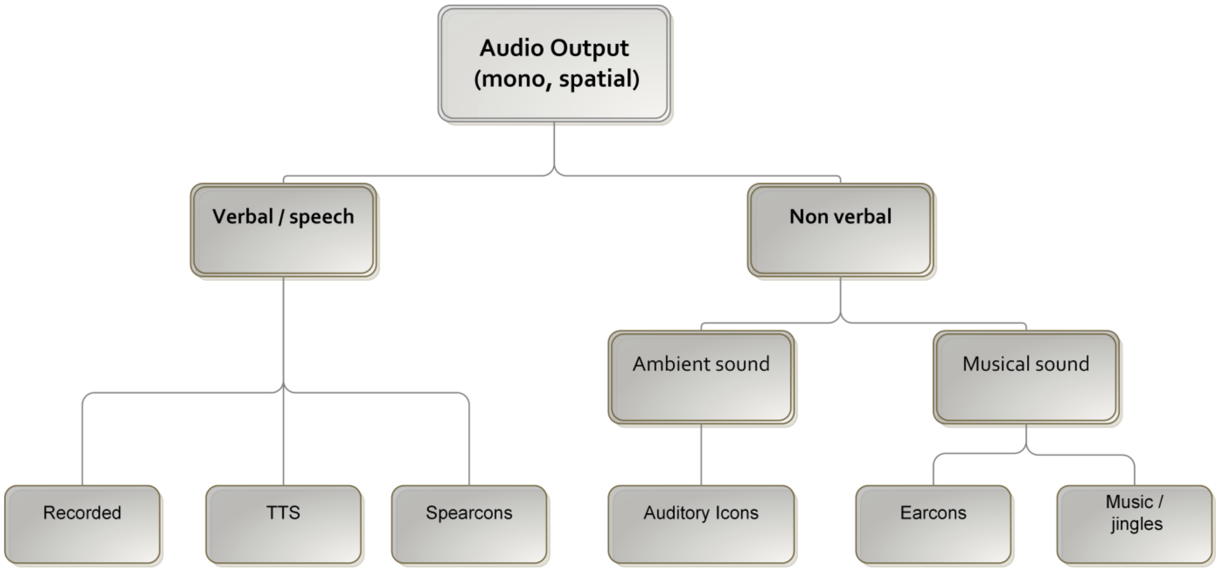


Figure II.18: Classification of audio output modalities as proposed by Truillet (1999), translated and extended by spearcons with permission.

Audio output is often associated with speech. Yet, non-verbal output can also be used to communicate information. We based the analysis of different auditory output modalities in interactive accessible maps on the schema proposed by Truillet (1999) as shown in Figure II.18. Indeed, the types of output that we found are speech, spearcons, auditory icons, earcons and music. Most prototypes use 2D audio output, but sometimes spatial sound is used.

II.4.4.1.a Speech

Our analysis revealed that speech is the auditory output type that was used the most often in interactive maps for visually impaired people (Bahram, 2013; Brock, Truillet, et al., 2012; Campin et al., 2003; Daunys & Lauruska, 2009; De Felice et al., 2007; Hamid & Edwards, 2013; Iglesias et al., 2004; Jacobson, 1998a; Jansson et al., 2006;

Kaklanis et al., 2013; Kane, Frey, et al., 2013; Kane, Morris, et al., 2011; Krueger & Gilden, 1997; Lohmann & Habel, 2012; Miele et al., 2006; Parente & Bishop, 2003; Parkes, 1988; Petit et al., 2008; Poppinga et al., 2011; Rice et al., 2005; Schmitz & Ertl, 2010, 2012; Schneider & Strothotte, 1999; Seisenbacher et al., 2005; Senette et al., 2013; Simonnet et al., 2012, 2009; Tixier et al., 2013; Tornil & Baptiste-Jessel, 2004; Wang et al., 2009; Weir et al., 2012; Yairi et al., 2008; Yatani et al., 2012; Zeng & Weber, 2010; Zhao et al., 2008). Verbal descriptions can transmit information about geographic elements, which on a visual map is usually represented in the form of printed text, and on a tactile map is usually represented as braille text. To go even further, verbal descriptions can communicate global spatial knowledge such as spatial relations of streets and landmarks (Lohmann & Habel, 2012). Indeed, speech and text have many similar properties as a means of communication, such as their sequential nature, their dependence on a specific natural language, and their demand for the user's full attention (Blattner et al., 1989).

In general, speech output can be generated through digitized, i.e. recorded speech, or through speech synthesis. Digitized speech is the assembly of recorded words or sequences to build phrases that match the required output (Truillet, 1999). In comparison, text-to-speech synthesis (TTS) is sound output created from a textual input. Truillet describes the phases of this process. In a pre-processing step, raw text is converted so that numbers and abbreviations are spelled out. Also, exceptions of pronunciations have to be handled. In the second step, the text-to-phoneme or grapheme-to-phoneme conversion, the text resulting from the pre-processing is converted into phonetic transcriptions. It is then divided into prosodic units, i.e. phrases and sentences. This process includes phonetic, phonologic, lexical, syntactic and semantic algorithms. The difficulty of the transcription depends on the language. In the next step, the phonetic and prosodic description is converted into auditory output. There are different algorithms for this conversion. In the best case the system takes into account the prosodic schema by detecting keywords such as articles, prepositions and conjunctions. Sometimes the length of groups of words is used to simulate pauses for breathing. This results in a natural intonation.

Three criteria appear important to determine the quality of synthetic speech output (Truillet, 1999). The first criteria is acoustic and prosodic sound quality which results from of a combination of factors, such as the degree of intelligibility of the generated message, i.e. if the interlocutor understands the message, but also its melodic and rhythmic accuracy, the naturalness of the voice, as well as subjective appreciation. Second, there is flexibility, i.e. the easiness to change the content of the messages with regard to the cost in time, human and material resources. Third, there is efficiency in terms of transporting the meaning. Digitized speech has the advantage of the voice being very natural and having a good prosody. To this regard, Petit et al. (2008) compared a version of their interactive map with TTS and one with recorded speech. They observed that participants understood the recorded voice slightly better than the synthesized voice. However, as every message needs to be recorded in advance, digitized speech is less flexible than synthesized speech. Also digitized speech requires more disk space. It is therefore best adapted for systems with little speech output which does remain stable over a long time. On the other hand, the flexibility of TTS systems comes with a higher algorithmic complexity (Truillet, 1999).

Visually impaired users probably present the largest user group for synthetic speech systems (Stent, Syrdal, & Mishra, 2011). As we described in II.1.4, the auditory capacities of visually impaired people differ from those of sighted people. For instance, they tend to prefer intelligibility of TTS over naturalness (Stent et al., 2011). It is therefore important to test text-to-speech synthesis specifically with this user group. Asakawa, Takagi, Ino, and Ifukube (2003) asked 7 legally blind people to evaluate listening speeds for linearly time compressed natural speech in Japanese language. They observed that novices were able to comprehend almost 100% of the text when TTS was 1.6 faster than the default value. Advanced users could still understand about 50% when TTS was 2.6 faster than the default value. In a study with 36 early-blind people, Stent et al. (2011) compared different TTS systems . They observed a significant effect of speaking rate as performance decreased, when speaking rate increased. Also, accuracy appeared to be higher for male than for female voices. Stent et al. also observed that participants under the age of 25 had the highest accuracy, and participants over 51 had the lowest accuracy. Furthermore, accuracy was positively correlated to frequency of using TTS systems.

Krueger and Gilden (1997) tried to speed up the speech output of their system by experimenting with audio abbreviations of the names of the states in the USA. They observed that the first syllables, for instance "Cal" for California, "Kan" for Kansas, and "Ken" for Kentucky, were not easy to distinguish from each other. However, they found that it was often faster and more understandable to say two different syllables (for instance, "rado" for Colorado, and "sota" for Minnesota). These audio abbreviations appeared quite easy to learn and use for familiar places.

Spearcons present an alternative idea (Walker, Nance, & Lindsay, 2006). They are spoken phrases which are sped up until they may no longer be recognized as speech. Thus, they are not simply fast spoken items, but distinct and unique sounds that are acoustically related to the original text. Spearcons are created automatically by speeding up the resulting audio clip from a TTS without changing pitch. Each spearcon is unique due to the specific underlying wording. Walker et al. observed 9 sighted participants using different auditory interfaces. Spearcons proved to be faster and more accurate than speech. In a study with 39 sighted participants, Dingler, Lindsay, and Walker (2008) observed that spearcons were as easy to learn as speech. Despite this promising results, so far spearcons have been very rarely used in interactive maps for visually impaired people (Su et al., 2010).

II.4.4.1.b Ambient Sound

Non-speech audio is a helpful cue in our daily life. As described by Stockman (2010), ambient sound is especially helpful for visually impaired people. For instance, they rely on the sound of cars to know when it is safe to cross a street. The richness of information that can be transmitted by sound has inspired the design of auditory icons (Gaver, 1989). Auditory icons are similar to visual icons. They are non-speech, non-musical sounds that present information by analogy with everyday events. The analogy can be symbolic, metaphorical or nomic. Symbolic mapping is arbitrary and relies on conventions for meanings, as for instance applause for success (Blattner et al., 1989). Metaphorical analogies are based on similarities such as a falling pitch for a falling object. Nomic analogies are based on physical properties, i.e. the sounds of the things they represent (Gaver, 1989). A well-known example is the sound of crumbled paper or shattering dishes associated with the computer's waste-bin.

Several interactive map projects have used auditory icons (Campin et al., 2003; Hamid & Edwards, 2013; Heuten et al., 2007; Jacobson, 1998a; Lawrence et al., 2009; Milne et al., 2011; Parente & Bishop, 2003; Pielot et al., 2007; Senette et al., 2013; Simonnet et al., 2009, 2012; Su et al., 2010; Zhao et al., 2008). Often auditory icons are used in combination with speech output. Only few projects (Heuten et al., 2007; Lawrence et al., 2009; Milne et al., 2011; Pielot et al., 2007; Su et al., 2010) made use of non-speech output only. Common auditory icons in interactive maps at the scale of a city use the sound of cars for representing streets, splashing water or waves for rivers and oceans and birds chirping for parks. In maps that represent regions and countries, water can also be associated with oceans and cars can represent entire cities. This demonstrates that the meaning of auditory icons is ambiguous and depends on the context.

Auditory icons are supposed to be intuitive to understand (Gaver, 1989). Yet, Dingler et al. (2008) observed that speech and spearcons were easier to learn than auditory icons. Walker et al. (2006) found that auditory icons were slower than speech. Even if these studies have been done with sighted people, similar results have been reported in the accessible interactive map studies. Petit et al. (2008) observed that the use of a metaphor for water was perceived as irritating. Lazar et al. (2013) report that a lot of users did not understand the sonification tones and preferred speech. Krueger and Gilden (1997) argue that many features such as mountains, rivers, lakes, etc. do not have unambiguous sound associated with them. These findings are in contrast with other studies, in which participants have successfully created mental maps from auditory icons (Heuten et al., 2007; Pielot et al., 2007; Su et al., 2010). These studies report that auditory icons are a successful means for supporting spatial cognition. Furthermore, haptic cues seem to be harder to identify than auditory icons (Lawrence et al., 2009). This may be explained by the fact that haptic cues in contrast to auditory icons cannot benefit as easily from analogy to everyday objects. Delogu et al. (2010) suggested that auditory icons are more adapted for exploring and learning the macrostructure of a spatial environment than for learning spatial details. As a conclusion, it is possible to create mental representations from auditory icons. Yet, the conveyed information is different than when speech is used. Learning the meaning of auditory icons is necessary.

II.4.4.1.c Music and Earcons

Music is another variant of non-speech audio output. Music is rarely used in interactive maps. Yairi et al. (2008) proposed the "One Octave Scale Interface". In their map prototype, when a user's finger follows the lines in the map, the notes of an octave ('do re mi fa sol la ti do') were played. The line was divided into eight segments that were associated with one of the notes and depending on the finger's position on the line the corresponding note was played. Therefore while advancing the finger on the line, continuous 'do re mi fa sol la ti do' sound was played and the rhythm of the octave depended on the speed of exploration. The idea was that users intuitively understand how their finger was positioned on a line and how long the remaining line was until the next crossing.

Earcons are a special variant of musical representation. They have been introduced by Blattner et al. (1989) as non-verbal audio messages in form of structured sounds. Earcons are based on motives, which are single pitches or sequences of pitches. Motives possess fixed parameters—rhythm and pitch—as well as variable parameters—timbre, register and dynamics. Timbre is the quality or "color" of a sound, register is the relative perception of high and low of a pitch or set of pitches, and dynamics is the relative loudness or softness. Linking different or identical motives leads to patterns. Thus there are one-element earcons and compound earcons. Motives can also build up a "family", i.e. a hierarchical group of motives. Members of the family can inherit parts of a sound. For instance, error sounds can begin with the same motive and end with varying motives to differentiate them.

Earcons, same as auditory icons, rely on an analogy to visual icons. However, as they do not rely on the analogy with real-life objects, as is the case for auditory icons, the meaning must be learnt. To this regard, Dingler et al. (2008) observed that earcons were slower to learn than speech, spearcons and auditory icons. Another aspect concerns speed of interaction. Blattner et al. (1989) recommended earcons to be as long as necessary but as short as possible. Walker et al. (2006) observed a slower and less accurate performance with earcons in comparison with speech. Likewise, in their interactive map project, Krueger and Gilden (1997) considered that earcons were too slow. They measured that it took one quarter of a second for clicks and pops and one second to play a percussive sound like a bell. However, earcons were still quicker than speech output, as for instance it took 1.5 seconds to say "Mediterranean Sea". Furthermore it is important to establish patterns that are understandable for the user. For instance, Schneider and Strothotte (1999) proposed a map prototype in which distances were coded through balance and pitch. Evaluations with one blind user showed that the proposed coding was too rough.

Earcons have been used in numerous interactive maps for visually impaired people (Carroll et al., 2013; Daunys & Lauruska, 2009; Iglesias et al., 2004; Kaklanis et al., 2011, 2013; Rice et al., 2005; Su et al., 2010; Tixier et al., 2013; Weir et al., 2012; Zhao et al., 2008). As for the auditory icons, often earcons are used in complement with speech. Su et al. (2010) combined the use of auditory icons and earcons, without speech output. Kaklanis et al. (2011) used only earcons. However, in their later prototype they combined the use of earcons with speech (Kaklanis et al., 2013). Despite the challenge related to learning the meaning of earcons, Delogu et al. (2010) have demonstrated that earcons could be successfully used for creating mental maps both for sighted and for visually impaired people.

II.4.4.1.d Spatial Sound

In some interactive maps the above described non-speech sounds (auditory icons or earcons) were presented in 3D, i.e. as spatial sound (Carroll et al., 2013; Heuten et al., 2007; Kaklanis et al., 2013; Milne et al., 2011; Parente & Bishop, 2003; Pielot et al., 2007; Zhao et al., 2008). Spatial sound is audio output perceived as if it originated from a point in 3D space. The idea is based on the fact that sound in a real environment is spatial and that a sound source can be localized. Nasir and Roberts (2007) argued that non-spatial sound is usually used to represent quantitative information and that spatial sound is better adapted for presenting (geo-) spatial information.

From a perceptual perspective, four effects contribute to the perception of spatial audio (Nasir & Roberts, 2007). First, Interaural Time Difference (ITD) is the phase difference between the sound arriving at the left ear compared with the right ear. Second, Interaural Intensity Difference (IID) means that objects which are closer are perceived as louder. Third, Doppler effects are frequency changes that indicate the movement of the object. Fourth, environment effects like reverberation, reflection and sound occlusion indicate positions of objects. ITD on its own allows the user to locate sound in the azimuth plane. ITD combined with IID allows the user to perceive the elevation of sound clues. Furthermore, the reflection of sound from the outer ear (pinna), head, hair, and torso and its path to the inner ear change the sound spectrum (Dramas, 2010). These differences are related to the morphology of the individual. They form a "signature" in terms of the overall sound reception that is unique and specific to each person.

To create a virtual spatial sound, two different sounds need to be generated in both ears (Dramas, 2010). Technically spatial sound can be created by headphones or surround sound speakers (Nasir & Roberts, 2007). Parente and Bishop (2003) reported that in their interactive map prototype they achieved a convincing separation of left and right, and a minor separation of front and back with standard headphones, inexpensive sound cards, and readily available spatial sound libraries. Yet, the quality of the simulation can be increased by using a Head Related Transfer Function (HRTF). HRTF models the specific sound reception signature related to an individual's body. It is created by placing a microphone in each ear of the person and analyzing changes between the emitted and the received sound. From this a filter is created, for the virtual sound production.

As we reported in subsection II.1.4, the auditory localization of objects is possible for visually impaired people, even if some studies found that it was impoverished (Cattaneo & Vecchi, 2011). In terms of the interactive maps, it has successfully been evaluated with visually impaired people (Heuten et al., 2007; Kaklanis et al., 2013; Zhao et al., 2008).

II.4.4.2 Touch

Touch output in interactive map prototypes is mostly used complementary to audio output. Nevertheless it plays an important role for presenting graphical information non-visually (Giudice, Palani, Brenner, & Kramer, 2012). As stated before, touch includes cutaneous, kinesthetic and haptic perception (see II.1.3.2). The definition of which modalities can stimulate touch perception is relatively vague. According to El Saddik et al. (2011), this category includes output from actuators which act as force and position source on the human body to simulate a tactile sensation. Other devices do not actively produce a force. Yet, through the manual exploration of a device, the user perceives kinesthetic information. This information contributes to the mental representation of space. In the following we present the analysis of the interactive map corpus, regarding cutaneous, kinesthetic and haptic output modalities.

II.4.4.2.a Haptic Reference Frame

We previously introduced the haptic reference frame (see II.2.2.2). It is difficult to classify the haptic reference frame as output interaction as it is not actively created by the system. The system rather inherently provides a stable frame. It is then through the kinesthetic perception from the user's movements within this frame that a mental representation is created. Nevertheless we consider that the haptic reference frame has such an important contribution to cognitive mapping that it should not remain unmentioned.

Not all devices provide a haptic reference frame. Keyboard interaction does not provide any perceivable relation between the hand movement and the movement on the map. Delogu et al. (2010) reported that keyboard exploration, being strictly symbolic and discrete, required more cognitive effort for reconstructing the position after each step. In comparison with touch interaction it was therefore slower.

Likewise, haptic devices do not provide a reference frame. Some haptic devices (like the Phantom) even provide 3 or more degrees of freedom. Integrating the third dimension into their mental representation may be challenging for visually impaired people.

The movement of a computer mouse is not linearly related with the movement on the map. Thus, differences exist between the perceived local distances and the global distances (Jetter, Leifert, Gerken, Schubert, & Reiterer, 2012). Also, users often lift the mouse and move it (Lawrence et al., 2009). Due to this behavior, disorientation can occur when operating the mouse without vision (Golledge et al., 2005; Pietrzak et al., 2009). In order to overcome this, Rice et al. (2005) included a haptic grid overlay and a haptic frame in their map, which was operated by a force feedback mouse. The haptic grating of the grid within the map produced haptic feedback and allowed users to maintain a sense of distance, scale, and direction. The haptic frame around the map served as a barrier to limit the map. Rice et al. (2005) reported that the frame was very helpful. Yet, Lawrence et al. (2009) observed that even with a similar grid system, spatial updating proved difficult for most participants.

Tactile actuator displays consisting of one or several braille cells do not provide a haptic reference frame. For instance for the Tactos device, tactile feedback was coupled with the kinesthetic movement, but users could never perceive the whole figure at the same time (Gapenne, Rovira, Ali Ammar, & Lenay, 2003).

On the other hand, tactile actuator displays with large matrices of pins that are explored with one or both hands provide a haptic reference frame (Schmitz & Ertl, 2012; Shimada et al., 2010; Zeng & Weber, 2010). Other displays that typically provide reference frames are touch-sensitive devices. Both display types provided absolute pointing coordinates in two dimensions and allows continuous finger movements within a fixed frame. The kinesthetic feedback from arms and fingers, combined with the position relative to the outer frame of the touch display, may benefit users' spatial awareness (Zhao et al., 2008). Also, for touch screens that are larger than a typical mouse pad the intensity of kinesthetic feedback is greater (Jetter et al., 2012). Consequently, Tan, Pausch, Stefanucci, and Proffitt (2002) observed a significant improvement of spatial recall by sighted participants when using a touchscreen in comparison with using a computer mouse. They reported that especially female participants benefitted from using the touchscreen. They explained the improvement with the kinesthetic cues from the touchscreen interaction as compared to interaction with a computer mouse. Of course this is of limited validity for touch-sensitive devices with smaller display size. A map displayed on a smartphone is limited in size and it may be necessary to scroll and zoom in order to explore the whole map, which makes it difficult to construct a mental map. Indeed, it has been shown for sighted people that spatial memory performance was higher when using a touch device than when using a mouse, but that this advantage vanished when panning and zooming were involved in exploration (Jetter et al., 2012). To our knowledge, there are no studies on spatial representations resulting from zooming and panning maps with regard to visually impaired people.

Prototypes that are based on image recognition equally provide a haptic reference frame. Indeed, in this case as when exploring a touchscreen, users are exploring a two dimensional surface. They do not perceive a difference related to the technology. The use of raised-line map overlays can provide additional tactile cues (see subsection Map Overlay). As an alternative to an overlay in form of a map, some prototypes included a generic grid with tactile dots as a position and direction aid (Krueger & Gilden, 1997; Schneider & Strothotte, 1999; Zhao et al., 2008).

Similarly, a haptic reference frame is also provided in tangible interaction, where an object is moved with regard to fixed delimitations (Milne et al., 2011; Pielot et al., 2007).

II.4.4.2.b Map Overlay

Raised-line maps have proved beneficial for spatial cognition in visually impaired people (see II.3.2.2.c). Some of the interactive map projects make use of this by augmenting the prototype with a raised-line map overlay (Brock, Truillet, et al., 2012; Campin et al., 2003; Hamid & Edwards, 2013; Miele et al., 2006; Parkes, 1988; Senette et al., 2013; Wang et al., 2009; Weir et al., 2012). The idea behind this concept is to provide the visually impaired map reader with a familiar interface. Yet, instead of overloading the tactile channel, information is partially provided through a tactile and partially through an auditory modality. The prototypes that include raised-line overlays in the interactive map corpus were based on touch-sensitive devices on which the raised-line map was placed as an overlay (see Figure II.19). We will refer to these devices as audio-tactile maps (see also VII.5.1).

Figure II.19: Placing a raised-line map overlay on a touchscreen.

As an alternative to paper-based raised-line overlays, Kane, Morris, and Wobbrock (2013) recently proposed "touchplates". Touchplates consisted in passive tactile sheets, visual tags and associated software for touch handling. The visual tag enabled the software to adapt to the touchplate's position. Touchplates have been produced with different materials and different methods, such as 3D printing or laser cutters. Touchplates can have holes in which touch interaction can occur, or if they are transparent the touch can be detected on their surface. Kane et al. proposed different touchplate sets, including overlays for keyboards, computer mice, menu bars or maps. These touchplates have been evaluated with a map application on a touchtable. The different touchplates were mapped to different applications. The results revealed user preferences regarding the different forms of touchplates. Participants particularly appreciated the fact that the user interface adapted to the touch plate position. As the aim of the study by Kane et al. was not the interactive map itself but evaluating the the touchplates concept, we decided not to include it in the corpus of interactive maps for visually impaired people.

Previous studies have identified benefits of raised-line maps for the cognitive mapping of visually impaired people (see II.3.2.2.c). It may be hypothesized that the benefits of raised-line maps for cognitive mapping also apply to interactive maps with raised-line map overlays. However, no conclusive study has been done so far.

II.4.4.2.c Vibro-Tactile Actuators

In vibro-tactile displays, vibrations are typically provided as feedback to actions performed by users, often in a virtual environment (Choi & Kuchenbecker, 2013). In the subsection dedicated to devices (II.4.2) we did not specifically mention vibro-tactile displays. This is because within the interactive map corpus, vibro-tactile information is used to augment other existing devices. Indeed, the advent of new smartphones and tablets with integrated vibro-tactile motors, provides the possibility to stimulate cutaneous perception through vibration (Giudice et al., 2012). Concretely, within the corpus of interactive maps all of the tablet-based prototypes and most of the smartphone-based prototypes made use of the integrated vibro-motors (Carroll et al., 2013; Poppinga et al., 2011; Senette et al., 2013; Simonnet et al., 2012). In contrast, Yatani et al. (2012) augmented a smartphone with a grid of 3x3 vibro-motors. This allowed localized vibrations.

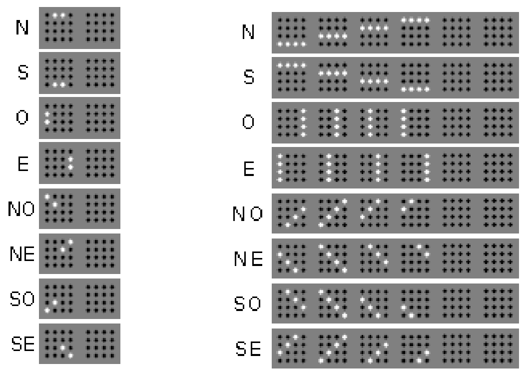
Choi and Kuchenbecker (2013) presented a comprehensive review of vibro-tactile displays, with regard to human perception as well as technical possibilities. They defined several aspects that impact the design of vibro-tactile displays. First, thresholds for perception of stimuli must be considered concerning the intensity as well as the frequency of vibrations. The second aspect is discrimination between different vibro-tactile cues. Choi and Kuchenbecker recommended at least 20%–30% of a difference in amplitude or frequency in order to achieve robust discrimination between vibro-tactile stimuli. The third aspect is the perceived intensity which depends both on amplitude and frequency of the signal. Fourth, there is the temporal discrimination of cues. As stated before (II.1.3.2), human tactile perception has a high temporal acuity. It is also good at discrimination and recognizing tactile rhythmic differences, i.e. changes in the amplitude over time. Finally, there are also qualitative differences in the perceived signal. Depending on the frequency and amplitude, the vibration can be perceived as slow kinesthetic motion, rough motion or smooth vibration. Brewster and Brown (2004) introduced tactons, also called tactile icons. Tactons are structured, abstract messages that make use of vibro-tactile sensations to convey information. Thus they are the tactile equivalent to icons and earcons. Similarly as earcons, the meaning of tactons is not analogue but has to be learnt. Advantages are that tactons are quicker to perceive than braille text and that they are universal and not bound to a specific language. Numerous tactons can be robustly distinguished (Choi & Kuchenbecker, 2013). Similarly as earcons, tactons possess different parameters that can be modified (Brewster & Brown, 2004). Concretely, these parameters are frequency (within the range of the perceivable frequencies 20 to 1000 Hz), amplitude (i.e. intensity), waveform and duration, rhythm. Furthermore, Brewster and Brown suggested that the location of the actuator with regard to the body could be used for coding the tactons. Within the corpus of interactive maps, vibration is presented at the fingertips of the user. However, other body parts can also perceive vibration and this has successfully been used in different prototypes (see for instance Heuten et al., 2008). Burch and Pawluk (2011) proposed to apply vibro-tactile feedback to multiple fingers in parallel. In a picture recognition task with visually impaired participants, they observed a higher accuracy and a decrease in response time when participants used three instead of one fingers if the objects were represented with textures. This is in line with studies on raised-line images, that observed a higher picture identification accuracy if five fingers rather than one were used in the exploration process (Klatzky et al., 1993). So far no interactive map project for visually impaired people has investigated this possibility, although it seems promising.

Within the corpus of interactive maps, user studies demonstrated that cognitive maps of participants were more accurate after exploring a smartphone with vibro-tactile and audio feedback than with audio feedback alone (Yatani et al., 2012). Furthermore, participants stated that it was quicker and easier to integrate information from both channels. However in a study on learning of non-visual graphical information a vibro-audio tactile interface proofed to be less efficient than raised-line drawings (Giudice et al., 2012). It can therefore be hypothesized that the perception of lines and curves is harder when presented through vibrations than when printed as raised-line drawing, but that it can be a helpful complement to audition. There is still a need for further investigation and comparison of vibro-tactile output with other output modalities.

II.4.4.2.a Raised-Pin Displays

Variants of raised-pin displays can be used for displaying graphical information. Some interactive map projects used dynamic displays in the size of one or two braille characters (Jansson et al., 2006; Tixier et al., 2013). In these prototypes users perceived a tactile feedback analog to the part of the shape over which the receptor field was located. In order to recognize a complete shape, the user had to actively move the receptor field of the device. Jansson et al. (2006) evaluated their interface with 60 sighted participants.

Their findings revealed that exploration was significantly quicker if the map was represented with "empty" forms, i.e. forms without texture filling. They observed that textures were confounded with borders and lines. As an alternative Pietrzak et al. (2009) proposed to apply the concept of tactons that has been developed for vibro-tactile displays to raised-line cells. They designed a set of distinguishable static and dynamic tactons for representing directional information with a VTPlayer tactile mouse (see Figure II.20). Each pin had two states, up and down. A pattern combined the states of several pins within a cell at a given time, thus forming static tactons. Beyond that, dynamic patterns included lists of patterns and durations which are associated with a certain tempo. They could be either blinking, i.e. alternating, or have wave forms, i.e. represent the evolution of a shape in space and time. It would certainly be interesting to investigate whether the concept of raised-pin tactons could be applied to interactive map exploration.



(a) (b)

Figure II.20: Set of Tactons for indicating cardinal directions as proposed by (Pietrzak et al., 2009). (a) Static Tactons. (b) Dynamic tactons. Concatenating the patterns in the colons leads to a wave form tacton.

Some of the interactive map prototypes made use of larger displays with actuated pins (Schmitz & Ertl, 2012; Shimada et al., 2010; Zeng & Weber, 2010). These devices display more information than smaller ones. The users then explore the display by moving their hands and arms, and thus perceive information in parallel. They then integrate the cutaneous with kinesthetic information However the rendering of information remains challenging as the resolution is lower than for a normal screen (Zeng & Weber, 2010). Schmitz and Ertl (2012) displayed streets as lines and buildings as rectangles. They proposed varying line size and filtering out details, in order to avoid overloading the map reader. Zeng and Weber (2010) proposed a tactile symbol set for displaying different types of information such as bus stops or buildings. In a second publication they further extended the tactile symbol set (Zeng & Weber, 2012).

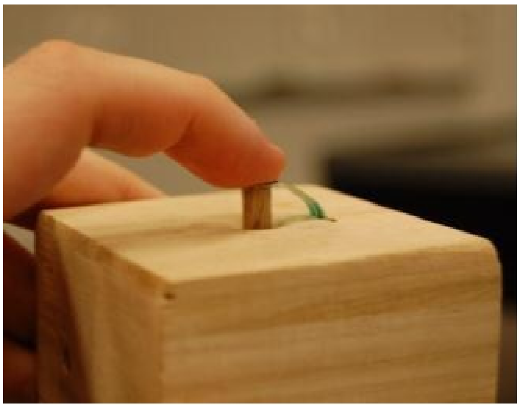
II.4.4.2.b Laterotactile Feedback

Laterotactile displays present another possibility to transmit cutaneous information. Within the interactive map corpus, two devices of this kind were used (Lévesque et al., 2012; Petit et al., 2008). In these systems tactile feedback was produced by a device that laterally stretches the skin of the finger. The sensations that could be produced were dots, grating (waves) and vibrational sensations. By doing so, simple shapes, textures and stroked paths could be displayed and successfully recognized by participants (Lévesque & Hayward, 2008). Furthermore, it has been demonstrated that shapes represented by dots or vibrations were easier to recognize than shapes represented by gratings. Finally, there was no significant difference in performance in recognition of tactile symbols between sighted and visually impaired people (Lévesque & Hayward, 2008). Further user studies with these devices showed that visually impaired people as well as blindfolded sighted people could successfully use this kind of output to explore maps (Petit et al., 2008). Levesque et al. (2012) observed 9 blind users while exploring a concert hall seat plan with this type of device. They proposed two interaction techniques to toggle the level of detail: automatic adaptation of detail level and manual toggle. These two interaction techniques were compared with a map a version with fixed level of detail. Levesque et al. did not observe a significant effect of detail level on exploration time and accuracy. However, participants preferred the manual toggle. Although few studies have investigated laterotactile output for accessible interactive maps, the existing findings suggest that this research direction is promising.

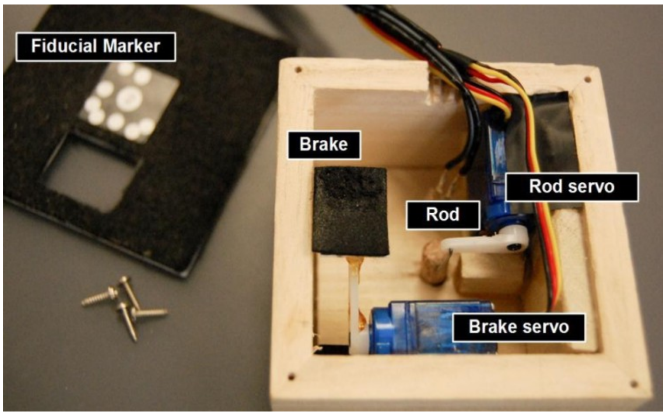
II.4.4.2.c Kinesthetic and Haptic Feedback

As discussed before (see II.1.3.2), haptic perception involves the combination of cutaneous and kinesthetic perceptions. Haptic devices use force-feedback to present kinesthetic sensations. Consequently, these devices work well for some aspects of touch, such as recognizing geometric properties of objects, but are less adapted for cutaneous perception, such as recognizing texture (Brewster & Brown, 2004).

The type of haptic device influences the interaction. For instance as reported above, some devices allow interaction with a single point while others allow sending different feedback with two fingers. It can be hypothesized that the integration of information from a single point of contact into an ensemble of information is cognitively demanding (Brewster & Brown, 2004). This hypothesis is supported by studies on raised-line picture reading in which better performance has been observed if more than one finger was used for exploration (II.3.2.2.b).



(a)



(b)

Figure II.21: Haptic Tabletop Puck. (a) User exploring a surface with the finger placed on the rod. (b) View of the insight of the puck with different actuators taken from below. Reprinted with permission.

Haptic devices such as the Phantom have been criticized for their low accessibility, high price and fragility (Simonnet et al., 2012). Consequently, the BATS project (Parente & Bishop, 2003) aimed to use consumer grade haptic devices with lower costs. They allowed a variety of devices, including mice, trackballs, joysticks, and gamepads capable of providing force feedback. Marquardt et al. (2009) introduced the "haptic tabletop puck" (HTP) as a device for rendering haptic feedback on a multi-touch table (see Figure II.21). The HTP consisted of a block within which a rod could be adjusted in height by a servo motor. The rod served at the same type as input (by using a pressure sensor) but also as output for rendering haptic feedback. Furthermore, a servo motor could push a rubber plate against the surface in order to introduce friction. The tracking of the position was done by the multi-touch table by following fiduciary markers on the HTP. Dynamic sinusoidal vibration with varying frequency or amplitude could be used for transporting information. The different sensations that could be perceived by making use of the combination of actuators included height, texture, softness and friction. Each HTP only had one single rod and thus only one contact point, but it was possible to use several devices at once. The HTP has been accompanied by a haptic touch toolkit (Ledo, Nacenta, Marquardt, Boring, & Greenberg, 2012). This toolkit provided an easy programming interface with access to the hardware, a behavioral layer and a graphical layer. The HTP has been successfully used in geographical map applications, where the topographical relief has been mapped to the height of the rod, different types of terrain to different textures and ocean temperature to vibration frequencies (Marquardt et al., 2009). To our knowledge this device has only been evaluated with sighted people without blindfold, with haptic feedback being a complement to vision. It would certainly be interesting to test whether visually impaired people could create a mental representation based on this device. Furthermore, it would be interesting to study whether the use of multiple devices instead of one positively impacts spatial cognition, as research on tactile image reading suggests (see II.3.2.2.a).

Several researchers have investigated the design of haptic effects that could be created with different devices. Within the corpus of interactive maps for visually impaired people, cues that were used in the BATS project included bumps at the boundaries of countries and states and constant vibrations on cities (Parente & Bishop, 2003). Lawrence et al. (2009) presented information via vibration with a force-feedback mouse. In a user study they compared haptic feedback to auditory icons. They observed that the haptic symbols were less easily understood than the auditory icons. Some users even experienced the haptic feedback as annoying. Lawrence et al. argue that this might be related to the limited range of available haptic cues in comparison to auditory cues. Differences between haptic signals were subtle and it was therefore more difficult to differentiate between different symbols. Golledge et al. (2005) presented different haptic effects that could be created with force-feedback devices. For instance, shapes could be defined as “virtual walls”. Passing the virtual wall with the device would demand an extra force of the user. On the other hand, following the outline of the virtual wall would reveal the shape. Golledge et al. suggested using this effect for boundaries of buildings. Multiple virtual walls can be used to build an effect of texture. This could be used to differentiate geographic regions. A “gravity well” effect could draw a cursor to the center of an object. Golledge et al. proposed using this effect for guiding the user to different regions on the map. “Rubber banding” make it easier to remain on the object. This effect could be used for facilitating following roads or borders. However, Golledge et al. also stated that identifying irregular polygons is difficult just by following the outline with the tactile sense. Furthermore, they suggested to represent texture through vibrations (see subsection II.4.4.2.c). Golledge et al. also reported that users tended to get lost during map exploration with haptic devices due to the missing haptic reference frame. Consequently, Rice et al. (2005) proposed to compensate for this lack of orientation, by introducing a frame with haptic feedback around the map. They reported that this frame helped users reorient themselves when they got lost during map exploration. Pietrzak, Martin, and Pecci (2005) studied haptic pulses with a Phantom device. They varied duration, amplitude and direction of the pulses. Their study revealed that directions were easier to identify than differences in amplitudes. The concept behind their study was to combine direction and amplitude alternation, in order to create haptic icons, as an equivalent to the previously mentioned earcons and tactons. It appears that there is need for further investigation on how to represent map information with tactile feedback.

II.4.4.3 Summary

In this subsection we presented different output interaction techniques that have been used in interactive maps for visually impaired people. We divided the techniques in the two categories audio and touch.

Audio output includes verbal and non-verbal modalities. We suggest that speech output is the most powerful means for communicating information as some information (e.g., names) can only be transmitted by speech or text. Yet, non-verbal output has also been used in interactive maps with controversial results. While it has been successfully used in some projects, other studies report difficulties for learning and recognizing the sound. Earcons demand more learning time than ambient sound. We suggest to use ambient sound and earcons to provide complementary information to speech. It also appears interesting to investigate the use of musical output. Finally, spatial information can be presented through spatial sound.

Touch output can be of cutaneous, kinesthetic and haptic nature. We suggest that for the exploration of spatial information, it is especially important to provide a fixed haptic reference frame. Vibro-tactile output seems to be a helpful complement for audio information. Yet, vibrations are often not spatially located and they proved less efficient for communicating graphical information than classical raised-line drawings. Raised-pin displays seem promising, especially if the display is large enough to be explored with both hands and provide a haptic reference frame. Yet, these devices are costly. A new possibility is provided by laterotactile displays. Although few studies have investigated laterotactile output for accessible interactive maps, the existing findings suggest that this research direction is promising. Many studies have investigated how (map) information can be displayed with haptic devices. Unfortunately these devices do not provide a fixed haptic reference frame. In conclusion, we argue that raised-line map overlays are highly adapted for presenting spatial information to visually impaired people. First, they rely on previously acquired map reading skills. Second, they also provide a fixed reference frame.

We suggest that non-visual interactive maps should at least provide speech output and best be combined with some sort of haptic feedback. More precisely we suggest using raised-line drawings. The speech output could also be combined with non-verbal audio output.

II.4.5 User Studies

In this section we present an analysis of the corpus of interactive map prototypes regarding experimental results. Several interactive maps for visually impaired people have been evaluated by users. Lohmann (2013) proposed a tabular classification of evaluations done with audio-tactile map systems for visually impaired people. Kaklanis et al. (2013) also reported experimental results for different prototypes. As their classifications are not based on the same corpus as our classification, we analyzed the papers in our corpus with regard to experimental results. However, not all papers included a user study. Furthermore we extended the corpus by papers that have been published on the same prototypes but with different user studies. For instance, Delogu et al. (2010) evaluated the prototype proposed by Zhao et al. (2008).

Several differences exist between studies. A first difference is whether the studies are of qualitative or quantitative nature. Some experiments report precise variables, a precise protocol and statistically analyzed results. However, a lot of papers report very vague information on the experimental protocol, observations and measures that were taken and results often are of qualitative nature (for instance "participants expressed positive feedback about the prototype").

Second, studies have various objectives. Many studies aim at evaluating the overall usability of the prototype, whereas others focus specifically on the spatial cognition resulting from its use. It has to be noted that usability can be assessed with quantitative measures for effectiveness, efficiency and satisfaction (ISO, 2010), but that these quantitative measures are rarely taken. Most studies observe only qualitatively whether users can successfully interact with the prototype. This is what we call "overall usability". Furthermore, spatial cognition can be part of usability as the spatial cognition that results from map exploration is a measure of its effectiveness. We believe that it is interesting to have a closer look at spatial cognition, for instance at the different types of spatial knowledge (landmark, route and survey). Therefore in this analysis we regard "overall usability" and "spatial cognition" separately. Furthermore we also classified experimental results on differences between populations.

Also, studies differ in the number of participants. Within the 30 papers that have reported experimental results the number of participants varied between 1 and 60, with the median being 8 participants.

Furthermore, some studies are done with blindfolded sighted people, others with visually impaired people. As reported before, spatial representations, behaviors as well as perceptual capacities differ depending on the visual capacities (see II.1.4 and II.2.2).

Although it is certainly helpful to evaluate with blindfolded sighted people, it cannot automatically be concluded that the results would be identic for visually impaired peers. However, as it is difficult to recruit visually impaired people it is not always possible to evaluate with them. Blindfolded sighted people are therefore helpful for evaluating concepts and opening up design space.

We classified the corpus with regard to these different aspects. However it has to be noted that comparison of user evaluations of different interactive maps is limited as prototypes vary a lot, in content, the used devices and interaction techniques.

II.4.5.1 Overall Usability

In the category "overall usability" we included mainly qualitative studies which observed if users were able to interact with the prototype and access spatial information.

Schmitz and Ertl (2010) asked four sighted blindfolded people to use their gamepad based map application. Participants succeeded in using the interface, but performance depended on expertise with using gamepads. It might be hypothesized that visually impaired people are less experienced than sighted peers, as there are few accessible videogames based on gamepad devices. It would therefore be necessary to evaluate the concept with visually impaired people in order to know whether it has an interest.

Other studies evaluated overall usability with visually impaired participants. Parente et al. (2003) observed that one visually impaired and three blind high school students successfully learnt the controls of the system and navigated towards cities on the map. Their system could be used with generic input devices. As the paper did not specify which device has been tested, the reported results are of limited interest. Su et al. (2010) let one blind user explore their smartphone-based interface with audio output. The participant found all points of interest on the map and exploration speed increased with experience. He also gave positive feedback. However, due to the small sample size these results are of course limited. Bahram (2013) observed 12 visually impaired people using his touchscreen based application. The users reported surprise, enjoyment and interest. This shows that visually impaired people are interested in touchscreen use, however it does not report any results about success. Zeng and Weber (2010) asked four blind people to evaluate accessibility and readability of map elements presented on a display with raised pins. Users were able to identify streets, crossings, buildings and directions. This finding suggests that displays with raised pins present an interest for map representation. Kane et al. (2013) asked five blind users to explore their application that was based on image recognition and verbal feedback. All participants were able to complete the tasks and were enthusiastic about the application. It therefore appears that image recognition can be successfully used in interactive maps. Krueger and Gilden (1997) observed five blind people using their application with auditory feedback and a tactile grid. All subjects were able to use the interface. Beyond that, they took basic observations of spatial cognition: two users could produce acceptable drawings of the environment (yet the term "acceptable drawing" remains vague). The haptic-audio prototype proposed by De Felice et al. (2007) was evaluated by 24 visually impaired people. Users appreciated the control to trigger vocal messages on demand. All but two participants were able to explore the entire range of application. Kaklanis, Votis, and Tzovaras (2013) observed 9 partially sighted, 5 blind and 18 normally sighted users testing their system with haptic and auditory feedback. Most participants agreed that the concept was innovative but needed adjustment. 58% of the participants declared their willingness to use the prototype for learning a map. Zhao et al. (2008) took quantitative measures. They let seven blind people evaluate their prototype which was based on keyboard input and auditory output. They measured that participants successfully completed 67% of the training tasks and 90% of the tasks on the following day. To sum up, these findings suggest that different devices can successfully be used in accessible interactive prototypes. However, the validity of most results remains limited due to small sample sizes, or the absence of quantitative measures and systematic analysis.

II.4.5.2 Spatial Cognition

Several studies investigated interactive maps and their contribution to spatial cognition. For spatial cognition it seems especially interesting to distinguish studies with sighted and studies with visually impaired people, due to the differences in spatial cognition of these two populations (II.2.2.2).

First we report the experiments with sighted people. Poppinga et al. (2011) asked eight sighted users to explore their smartphone application with vibration and audio output and draw a map of the perceived environment during the exploration phase. They compared two zoom levels and observed that the "zoom in" condition resulted in a more accurate drawing than the more distant zoom condition. Participants correctly perceived basic information and relations. Also, Poppinga et al. hypothesized that the task was cognitively demanding as participants needed up to 15 minutes for drawing the map which was not large. Lohmann and Habel (2012) let 24 sighted blindfolded people compare two map conditions of a haptic prototype with speech output. In a first condition only names of landmarks and routes were indicated. In a second condition, supplementary information on the relation of geographic objects was provided. In the second condition, participants were able to answer more questions on spatial knowledge correctly. However, the result also depended on the type of spatial knowledge. Landmark scores showed a larger difference between the two conditions than route scores. Two studies have observed spatial cognition that resulted from tangible interaction. Pielot et al. (2007) evaluated a tangible user interface with spatial audio output with 8 blindfolded sighted participants. Their study showed that the tangible interface could be used to determine the position and orientation of the virtual listener (represented by the tangible object) with only small deviations from the real orientation. Furthermore, they discovered that users spontaneously rotated the tangible object to determine the spatial location of objects. It depended on the type of source how well the rotation could be used for determining orientation. Milne et al. (2011) compared a version of their prototype with tangible interaction and a version with body-rotation with 5 blindfolded sighted participants. They observed problems related to the shifting of reference frames between egocentric and allocentric perspectives. As tangible interaction has rarely been proposed for visually impaired people it would indeed be interesting to reproduce both studies with visually impaired participants.

Other studies were done with blind participants. Simonnet et al. (2012) let one blind user explore an interactive map prototype—a tablet application with auditory and vibrational feedback—and draw a map of the explored environment. They observed that the resulting map drawing was relatively precise. However, the result is of course of limited validity due to the small sample size. In another study, Simonnet et al. (2009) let two blind sailors learn a maritime environment with a haptic device and then navigate at sea in the same environment. Their study revealed that getting lost in egocentric mode during exploration of the virtual environment forces the blind sailor to coordinate his current view with a more allocentric view. It was therefore advantageous for constructing an allocentric representation. If this is the case, virtual environments can indeed be used as training environments. Getting lost and consequently exploring the environment with the objective to find one's way back, seems less stressful in a virtual than a real environment.

Heuten et al. (2007) let eleven blind users explore their application—a purely auditory map—with the objective to understand spatial relations and distances between objects. Users perceived the exploration as easy, except for the identification of objects' shapes. Also they observed confusions when two similar objects were close because of the similar auditory feedback they emit. Yairi et al. (2008) asked four blind people to explore their application with musical feedback and then walk the route unaided. All participants reached the goal, even if one was unsure about it. Even if people made wrong turns at cross points or felt lost, they were able to correct their route. Both studies show that non-verbal audio feedback can effectively be used for creating mental maps.

Yatani et al. (2012) let ten blind and two low-vision participants explore their application and then asked them to draw sketches. The application was compared in two conditions: smartphone with auditory output and smartphone with auditory output and additionally feedback through 9 vibrational motors. Even if all participants could understand the spatial tactile feedback, drawings were more accurate after audio and haptic feedback than after audio feedback alone. This study is in line with Giudice et al. (2013) who reported that different sensory sources led to composite representations that were insensitive to the origins of the knowledge. Beyond that, it suggests that the mental representations created from multiple sensory sources may be more complete than those created from one source alone.

Jacobson (1998a) asked five visually impaired and five blind people to evaluate his application—a touchpad application with auditory feedback. He analyzed verbal descriptions, map drawings and qualitative feedback and observed that all users successfully created mental representations from the map usage. Besides, they found interface simple, satisfying and fun. In another study, Jacobson (1996) compared route learning with a mobility instructor versus with a touch-sensitive interactive map and audio beacons. Verbal descriptions, sketch recall, distances by ratio-scaling, tactile scanning assessment and talk aloud protocol revealed that both groups were able to complete the route and verbally describe it. All sketches showed a high degree of completion and correctness but the group who had explored the interactive map was more accurate. Participants also provided positive qualitative feedback. This is in line with studies that revealed an advantage of tactile map use over direct exploration (see II.3.2.2.c). It can therefore be hypothesized that interactive maps as well as tactile maps are helpful tools for acquiring spatial cognition. However, so far no study directly compared these two map types.

II.4.5.3 Comparing Different Populations

Few studies have investigated the differences between parts of the population. Wang et al. (2012) compared the use of an interactive map (based on touchscreen and raised-line map with audio output) to a tactile map (without braille) by 6 blind and 6 sighted users. They observed that the blindfolded sighted participants were less efficient in route tracing than the blind participants. Petit et al. (2008) compared 20 sighted adults, 10 visually impaired adults and 10 visually impaired children while exploring a tactual actuator interface. Their study reveals that participants with visual impairment, especially children, liked the device and performed well. They did not observe any difference between sighted and visually impaired people regarding exploration time but between perceived easiness with an advantage for visually impaired people. Furthermore, children were faster than adults. Delogu et al. (2010) observed 10 congenitally blind, 10 late blind and 15 blindfolded sighted while exploring an interactive map based on the use of earcons. Their study did not reveal any significant difference between sighted or blind people in the accuracy of the resulting mental map. Yet, blind subjects reported to be helped more than sighted subjects by the fact that the sonification was spatial. Furthermore, both early and late blind participants rated the interface easier than sighted users. According to Delogu et al. both findings could be explained with the greater experience of visually impaired people with non-visual interfaces.

II.4.5.4 Summary

Numerous interactive map projects exist and different evaluations have been done with interactive maps. We classified these evaluations according to overall usability, spatial cognition, and comparison of different populations. As there is a large variety among the map projects regarding devices, interaction techniques and content, it is hard to compare the results.

To sum up, the different studies demonstrate that various types of devices and interaction techniques seem advantageous for acquiring spatial cognition. No study systematically compared different map types, so that there is no knowledge whether certain types of maps are more advantageous than others. Even if it is possible to create mental images from one sensory source (e.g., audio output), results suggest that feedback from more than one sensory modality may enhance the mental representation. Yet, further studies would be necessary. Also, studies suggest that interactive maps could have the same positive impact on spatial cognition than tactile maps. Again, there is a need for further investigation.

It has to be noted that many studies only report qualitative results and that the experimental setup and protocol often remains vague. Additionally, some studies have limited validity due to the low number of participants. Moreover, some studies are done with sighted and others with visually impaired people. Comparing the results between both groups is delicate, as it is known that perception and spatial cognition depend on visual capacities. However, as it is difficult to recruit visually impaired participants, testing with blindfolded sighted people remains an interesting means to evaluate concepts and open up design space. In general a lot of positive feedback has been reported on interactive maps and it appears that they are a promising solution for improving accessibility of geographic information. However, there is a need for more systematic studies for evaluating the proposed solutions.

II.5 Conclusion

In this chapter we presented the broad theoretical context that concerns interactive maps for visually impaired people.

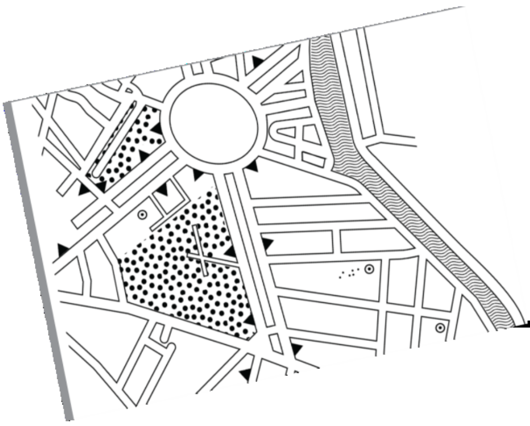
We started with a presentation of visual impairment, indicating the classification of the World Health Organization on Visual Impairment. We underlined the social impact of visual impairment on activities and participation, and especially mobility and orientation. We also presented the large heterogeneity among the visually impaired population. Furthermore we compared the differences between the human senses. We also discussed the impact of absence of vision on perception.

In a second part of the chapter we specifically investigated spatial cognition, both for sighted as for visually impaired people. We first introduced definitions concerning spatial cognition and cognitive mapping. We defined landmarks, routes and survey knowledge as different types of spatial knowledge. We argued that it is possible to create mental representations from different sensory inputs. Therefore, visually impaired people are capable of acquiring spatial knowledge but their mental representations vary from those of sighted people. We also presented strategies of exploring space without vision. In addition, we underlined the importance of inter-individual differences on the discrepant data in studies on spatial knowledge. Finally, we presented methods for evaluating spatial knowledge.

In a third part, we focused on maps as tools for acquiring spatial cognition without vision. We underlined that maps can be helpful tools for improving orientation skills. We compared maps to other tools such as verbal guidance, small scale models and GPS-based navigation systems. Then we investigated the cognitive mapping related to map reading both for sighted and visually impaired map readers. Traditionally, maps for visually impaired people are tactile maps. We demonstrated that different haptic exploration strategies influence the result of raised-line image exploration. Furthermore, different studies, which have proved the interest of tactile maps for visually impaired people, have been presented. Then we detailed the methods related to drawing and producing tactile maps. Although tactile maps are efficient means for the acquisition of spatial knowledge, several limitations and problems are associated with them. We argued that therefore interactive maps are an interesting means of improving usability of maps for visually impaired people.

In the next subsection, we responded to Research Question 1 by opening up the design space of interactive maps for visually impaired people. We presented a classification of accessible interactive maps with regard to non-visual interaction. More precisely, we studied devices that have been used in the different prototypes. Then we detailed input interaction. More specifically we investigated speech recognition as audio input and touch input. We argued that gestural interaction may be a promising means of making touchscreens more accessible. Furthermore, we described output interaction. Acoustic output interaction included speech, ambient sound, music and earcons, as well as spatial sound. Touch output included haptic reference frames, map overlays, vibro-tactile actuators, raised-pin displays, laterotactile displays and kinesthetic and haptic displays. We conclude the chapter with an investigating of different user studies on interactive maps for visually impaired people. Further information on terminology, origin of the projects, timeline, and map content can be found in the appendix.

The acquired knowledge from this chapter will serve as a basis for the following chapters.



Chapter III

Designing Interactive Maps with and for Visually Impaired People

III Designing Interactive Maps with and for Visually Impaired People

This chapter details our contribution with regard to the design of interactive maps for visually impaired people. In this chapter we introduce our design choice, and present methods that have been employed during the design cycle as well as the resulting prototypes.

In particular it answers Research Question 1 (What is the design space for interactive maps for visually impaired people? What is the most suitable design choice for interactive maps for visually impaired people?) Regarding these questions we based the design of our prototype on the previous analysis of the design space as presented in chapter II. We then present the iterative implementation of this prototype towards the realization of an experimental prototype.

This chapter also answers Research Question 2 (How to involve visually impaired people in a participatory design process?). Participatory design includes users during the whole design process, but many of its methods are based on the use of the visual sense. During this PhD work, we have been facing many situations where the classic participatory methods were not adequate. Here, we first introduce this process and then report how we adapted the design process. We detail the contribution for each of the four steps of this design cycle: analysis, creation of ideas, prototyping and evaluation. As participatory design is an iterative process, several implementations of prototypes have been developed and continuously evaluated with visually impaired users.

This chapter also presents the material and methods for the user study in the following chapters IV and V.

III.1 Designing with Visually Impaired People

III.1.1 Usability and Accessibility

Usability is an important notion in Human-Computer-Interaction. It is defined as "the extent to which a system [...] can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" (ISO, 2010). Usability therefore depends on users, goals and context of use (Petrie & Bevan, 2009). It is not associated with the product in itself, but with the interaction between the user and the product (ISO, 2003).

When developing for users with special needs, as for instance visually impaired people, the notion of usability becomes even more important. Accessibility is defined as usability of a product, service, environment or facility by people with the widest range of capabilities (ISO, 2003). Accessibility is about designing user interfaces that more people can use effectively, efficiently and with satisfaction, in more situations (Henry, 2007). The ISO standard (2003) specifically states that the concept of accessibility addresses the full range of user capabilities and is not limited to users who are disabled. People without impairments can be temporarily handicapped—for instance when forgetting one's glasses—or be in a situational impairment—for instance when sunlight is reflecting on a display (Henry, 2007). Accessibility comprises these situations. Therefore, for Stephanidis (2009) accessibility is a prerequisite for usability.

III.1.2 Participatory Design and Accessibility

User-centered design, also called human-centered design, is a design process that focuses not on the technical possibilities but on satisfying the users' needs and obtaining a high usability (ISO, 2010). In user-centered design, the user has a distinct role from the researcher and the designer. Users are not included in the design process. However, designers and researchers closely study users' needs and take them into account in the design process. In comparison, participatory design goes a step further. Users participate directly and proactively in the design process (Sanders, 2002). As an example, user-centered design proposes evaluating systems by usability experts based on heuristics or guidelines, whereas in participatory design users themselves evaluate the system.

User-centered design and participatory design are close in their development cycle. Different sources define them as processes that are composed by several phases. However, there seems to be no common consensus on the precise nature of these phases. The ISO standard 9241-210 (ISO, 2010) defines four steps: 1) understanding and specifying the context of use, 2) specifying the user requirements, 3) producing design solutions, 4) evaluating the design. Similarly, Mackay (2003) applied a design process in four steps: 1) observe the user, 2) generate ideas, 3) prototype design, 4) evaluate system. In comparison with the ISO standard she reduces the analysis of users and context to one design phase, and introduces a supplementary phase for generating ideas that is distinct from the prototyping phase. Henry (2007) proposes a separation in three steps that are analysis, design and evaluation, thus contracting phase 1 and 2 of the ISO standard into one phase. Petrie and Bevan (2009) extend Mackay's proposition by introducing a fifth phase that is integrating the design into a finished application. This step is supposedly important in an industrial environment where a final functional prototype is demanded, but not necessarily in a research project. The different propositions agree in that there should be at least three phases: a first phase of analyzing users' needs and the context, a design phase and an evaluation phase. In any case all definitions agree that user-centered design and participatory design are iterative design processes. Iteration can be done for each step or for the entire process at a macro-level. Iteration means that specifications and prototypes are revised when new information is obtained in order to ensure that users' needs are met.

A variety of techniques can be used for implementing the participatory design process. Kuhn and Muller (1993) presented a taxonomy of different participatory design techniques. For user-centered design, techniques are defined by different ISO standards (ISO, 2002, 2010). A lot of these techniques are based on the visual sense. As an example Sanders (2002) mentions MakeTools that serve for generating and sharing ideas between different people, such as collages, drawings or models. The visual techniques and tools remain inaccessible for visually impaired users, thus making it difficult to include them in the participatory design process. However, it is important to include accessibility considerations into the development process from the beginning, and not apply them as a patch to a final product (Zimmermann & Vanderheiden, 2007). It is therefore necessary to adapt the participatory design process, to make it accessible for people with special needs (Henry, 2007).

III.1.2.1 Accessible Design Process

Different terms exist for describing the inclusion of impaired and older users and their needs in the design process, such as universal design, design for all, barrier-free design, inclusive design, (Petrie & Bevan, 2009), universal access, user interfaces for all (Emiliani, 2009), user sensitive inclusive design or accessible design (Newell & Gregor, 2000). All these terms refer to the practice of designing products that can be used effectively and efficiently by people with a wide range of abilities and disabilities operating in a wide range of situations (Vanderheiden, 2012). They suggest that all users should be included in the design process, and that this should be a proactive design concern more than an afterthought (Emiliani, 2009). According to Newell and Gregor (2000) it is an attitude of mind rather than simply mechanically applying a set of "design for all" guidelines. Small distinctions between different terms exist, but sometimes preference is more due to geographic location. For instance "universal design" is more widely used in North America, whereas "design for all" is more common in Europe (Petrie & Bevan, 2009). However, some authors make further distinctions between the different terms. For Stephanidis (2009) "universal design" focuses on shaping new technology rather than fixing existing one. For Vanderheiden (2009) "universal design" is not the process of creating products that everyone can use but ensuring that designs can be used by as many people as is practical. In comparison, Newell and Gregor (2000) distinguish between "mainstream design" (design for everyone except people with impairments), "assistive technology" (only for people with impairments) and "design for all" (including all users). The latter is a very difficult, if not often an impossible task. Providing access to people with certain types of disability can make the product significantly more difficult to use by people without disabilities, and often impossible to use by people with a different type of disability. Products designed for all must be capable of accommodating individual user requirements in different contexts of use, independent of location, target-machine and runtime environment (Emiliani, 2009). Even if elderly and disabled persons are included in the mainstream design process, it is not possible to design all products and devices so that they are usable by all people (G. C. Vanderheiden, 2012). One of the challenges in universal design is thus to recognize the full range of users who might be interested in using a particular system (Petrie & Bevan, 2009).

Including impaired users in the design process raises specific challenges (Newell & Gregor, 2000). Impaired users may have very specialized and little known requirements. It may be difficult to get informed consent from some users. Besides, participation in the development of new assistive or design for all technology may raise disappointment among participants. Newell and Gregor underlined that some research may show that certain techniques are not successful, and that even if the research is successful, the user who was involved in the research may never personally benefit from the outcomes of the research. They also emphasize the importance of including users but not in a dominant role, i.e. leaving the establishment of the research agenda to the researcher. Finally, Lévesque (2005) argued that while it is useful to include the blind into the design process, designers of innovative devices must be ready to face a natural opposition to changes that contravene existing conventions. Yet, going against accepted ideas may lead to interesting and innovative results.

III.1.2.2 Making the Process Accessible for Visually Impaired People

In the continuation of this quest for accessible design, the next question is how concretely participatory design can be transformed into universal design. Henry (2007) proposes accessible methods for analyzing, designing and evaluating with users having different kinds of impairment. Zimmermann and Vanderheiden (2007) propose an accessible design process that combines accessibility guidelines with existing tools in software development. This process aims to integrate accessibility in mainstream products within existing product development practice.

Few publications exist on participatory design with visually impaired people. Henry (2007) provides some recommendations that concretely focus on visually impaired people. Participatory design with visually impaired people served for constructing sonified haptic line graphs (Ramloll et al., 2000). In this project, users influenced design from the design idea generation phase, through prototype implementation, and user-testing phase. Serpa, Oriola, and Hermet (2005) based the development of a vocal appointment manager on a participatory design cycle with visually impaired people. Concretely visually participants contributed to the design through brainstorming sessions. Sánchez (2008) developed games for blind children through a user-centered design process. He involved 67 school children as well as special education teachers and usability experts. The design process in this project was based on four phases (analysis, design, implementation and validation) and focused on usability as well as cognitive aspects. A participatory design process with visually impaired users has also been applied for the development of a low-fidelity near environment awareness component (Kim, Smith-Jackson, Carroll, Suh, & Mi, 2009). The project team was composed of visually impaired consultants and sighted researchers. Three design sessions served for discussing the concept, demonstrating intermediate prototypes and discussing the experience. Wagner (2010) presents an accessible design process for developing interactive maps in an educational context. He did passive observations during class sessions. Furthermore, he did interviews and group workshops held together with mobility trainers, teachers and visually impaired students were implemented during his project. An already existing interactive map prototype served as reference in early discussions. Tixier et al. (2013) developed their prototype in collaboration with a local association for visually impaired users. Two blind women have been involved in a six months field study, involving interviews and weekly design sessions. Finally, Lazar et al. (2013) developed a prototype of an interactive weather map in close collaboration with nine blind people and one sighted meteorologist. Their development process included interviews and surveys, user scenarios and user evaluations.

To conclude, even if some projects worked on accessible participatory design, there is still a lack of concrete methods and systematic techniques for making participatory design accessible for visually impaired users. For instance, few projects propose methods for creating ideas such as accessible brainstorming. In addition, there is little convergence in the design methods that have been chosen or in the number of participants between different projects. This is why in this project we investigated how to make the participatory design process more accessible to visually impaired people.

III.2 Adaptations and Results of Participatory Design with Visually Impaired Users

In this section we propose an adaptation of the participatory design process for working with visually impaired people. Although this was not our initial research question, we quickly experienced the need for working on accessible participatory design. We present how we recruited participants, how we communicated with them and how we arranged the logistics.

Concretely, our design process was iterative and composed of four phases. The analysis phase allowed us to identify users' needs for orientation and mobility, challenges that they face when traveling, and the reading of tactile maps. We also analyzed the literature on different design concepts and technical aspects. In the second phase, the generation of ideas, we proposed brainstorming and "Wizard of Oz" techniques as means for stimulating creativity. In the third phase, prototyping, we iteratively developed prototypes. In the fourth phase, evaluation, we developed evaluation methods for a user study. The experiment itself will be presented in chapter IV.

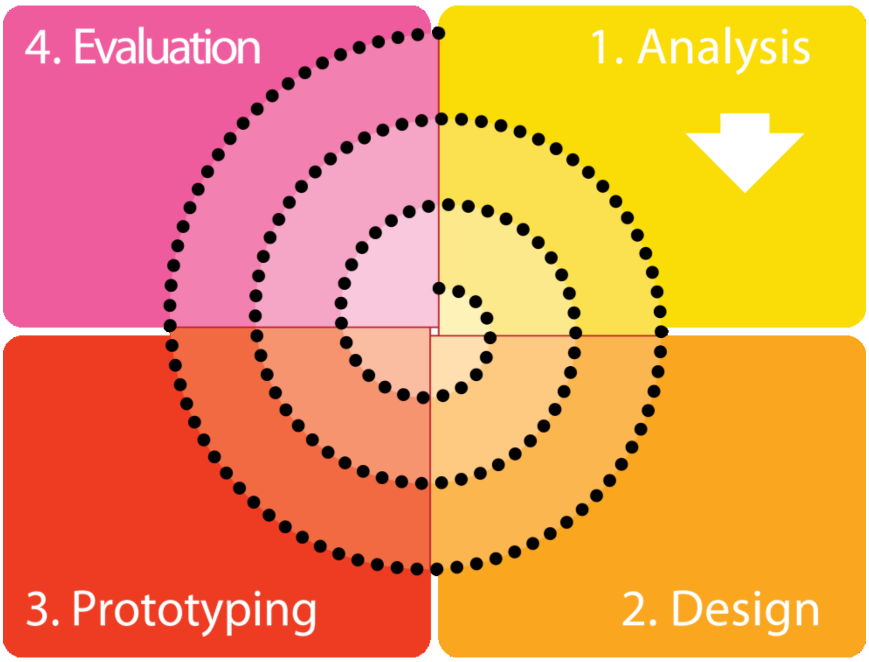


Figure III.1: Participatory design cycle as applied on our project. The cycle was iterative and composed of four phases (analysis, design, prototyping and evaluation). Translated and reprinted from (Brock, Molas, & Vinot, 2010).

III.2.1 General

The design process for our interactive map prototype was based on participatory design. As stated above, different approaches exist for participatory design. As depicted in Figure III.1, we chose the four steps proposed by Mackay (2003): 1) analysis phase (observe use), 2) design phase (generate ideas), 3) prototype design, 4) evaluate system. In this regard, our approach was also similar to that proposed by Sánchez (2008).

Participatory design is an iterative process (ISO, 2010). We implemented iterations in the design process both at micro scale, i.e. for each design phase, as well as at macro level, i.e. by developing several prototypes. User evaluations after completion of each prototype allowed us to improve the next prototype version. Evaluating throughout design is especially important when working with people with special needs (Henry, 2007). By doing so, we did not pursue a design approach that is focused on technological possibilities but rather on users' needs. The development of new technology is the goal of the process. But technology in form of different prototypes is also a tool for the participatory design process. Exploring the design space by including users throughout the process was more important to us than a perfectly functional prototype as final result.[13]

III.2.2 Participants

Participatory design demands close collaboration with users. Our aim was not "design for all", but developing assistive technology for visually impaired people through an accessible design process. One of the challenges was identifying the accurate user group. There is a large variety of visual impairments. Achieving usability for blind people does not mean achieving usability for people with low vision (Henry, 2007). Likewise, the ISO standard 16071:2003 (ISO, 2003) gives different recommendations for working with people with low vision and people with blindness. In our project we focused on legally blind people.

Some criteria for selecting participants apply to all types of user groups, such as age or gender. When working with visually impaired people, additional criteria are important. Examples are the degree of visual impairment, the proportion of lifetime with blindness or the age at onset of blindness, autonomy in everyday life, braille reading skills or use of assistive technology (Cattaneo & Vecchi, 2011). We applied these criteria in the selection of our participants.

Another aspect concerns working with experts versus working with novices. According to Henry (2007) it is advantageous to include experts in the beginning of the design process as it is possible to learn a lot from them. Novices can then evaluate the prototype. From our experience it is difficult to recruit visually impaired people and there is not always a choice concerning user's characteristics. Visually impaired users

[13] Our contribution to the participatory design cycle is partially published in (Brock, Vinot, et al., 2010).

that volunteer for participating in an experiment on new technologies are often rather experienced with using them, which means that recruiting novices is especially complicated. Furthermore, we have noticed that due to participating in the experiments some of the visually impaired users have become even more experienced. For instance, in the beginning we observed quite a high anxiety concerning multi-touch displays. Recently, some visually impaired users in our user group have acquired smartphones. The fact that visually impaired people get used to multi-touch interaction in their daily lives, then makes it even more interesting to include this interaction in assistive technology. In any case, we benefitted from the fact that one of the members of our project is himself visually impaired. He was involved throughout the whole project and contributed with a lot of ideas. He was also always available to evaluate the accessibility of technology before inviting participants for user studies.

In total we worked with 38 visually impaired people. In the beginning, participants for our project were recruited among the user group of the Navig project (Navigation Assisted by artificial vision and GNSS, Katz et al., 2012)[14]. The panel for this project was composed of 17 blind people of whom 8 were very involved in the project. In later project phases, we recruited 21 further participants through various methods; from students and employees of the "Institut des Jeunes Aveugles" (Institute for the Young Blind[15], Toulouse, France) and an associated manufacture, through an announcement in the newsletter of the Valentin Haüy association[16] in Toulouse, through a local radio broadcast for visually impaired people, and finally by word-of-mouth. Recruiting users through organizations, mailing lists and word-of-mouth has also been proposed by Henry (2007). On the basis of the collaboration with the Institute of the Young Blind, a joint laboratory—LACII[17] (Laboratoire Commun IJA-IRIT)—has recently been created.

Participants in our user studies were all blind with at most light perception, i.e. classified in the categories 3 to 5 as defined by the WHO (2010). This decision was made as the diversity of visual impairment is very large (II.1.2.1) and thus hard do study. For brainstorming sessions and pretests we also accepted people with residual vision if no other participants could be recruited. Etiology of the impairment was diverse, resulting either from congenital disease, accidental disease, or trauma. The user group was also diverse concerning the age at onset of blindness. Most of the participants were either

[14] Navig was a project between different institutions investigating safe navigation and object localization for visually impaired people (Katz et al., 2012).

[15] http://www.ijatoulouse.org/ [last accessed May 14th 2013]

[16] http://www.avh.asso.fr/rubrics/association/association.php?langue=eng [last accessed May 14th 2013]

[17] http://www.irit.fr/LACII/ [last accessed August 6th 2013]

working or in training, which is not surprising given the close contact with the Institute of the Young Blind. In early phases of the project we also included locomotion trainers of the Institute for the Young Blind to obtain information on orientation and mobility training for visually impaired people.

III.2.2.1 Communicating with Participants

Accessible communication tools can be used during the recruitment process and for exchanging information. From our observations 'Google Sites'[18] is accessible as a website to share information with users. 'Doodle'[19] is accessible and adapted for selecting dates when several people are involved. However, the poll should be kept simple. For instance, including yes-no-maybe options decreases the accessibility. We observed that 'Google Calendar's'[20] accessibility is limited. A lot of visually impaired people nowadays possess access to new technology including email and mobile phones so that it was easy to communicate with them.

It is necessary to get used to interacting with visually impaired people when meeting them for the first time. Henry (2007) recommends introducing the speakers orally. From our experience it is advantageous to seat people with some distance to facilitate oral identification. It is especially important to keep the seating arrangements fixed during the meeting. Speakers can then be introduced following the seating order. We limited the group size for brainstorming and discussion sessions to ten people, as above this number it gets difficult to identify speakers. Henry also suggests explaining activities and noises such as when objects are moved. Furthermore Henry proposes leading the participant to the room by offering the elbow or giving directions on where to find the chair.

Feedback from studies is often obtained through questionnaires. It is possible to make questionnaires accessible through technology (for instance with 'Google Forms'[21]). However, we observed that it is easier to present these questionnaires as interviews. In the case of Google Forms, even if the questionnaire itself is accessible with a screen reader, it can accidentally be submitted through pressing the enter button. In addition, users who are less expert in using new technology get reassured by having a direct interlocutor.

[18] https://sites.google.com/ [last accessed July 5th 2013]

[19] http://www.doodle.com/ [last accessed July 5th 2013]

[20] https://www.google.com/calendar [last accessed July 5th 2013]

[21] http://www.google.com/drive/apps.html [last accessed July 5th 2013]

We observed that participants in our study got attached to the researchers they knew and felt more confident with them. It was perceived as negative if researchers changed regularly (for instance students that left when their project ended). It seems at least necessary to explain to the participants why their contact person changed. We observed that for some people it is more difficult to share details on their impairment with a stranger (i.e. the researcher) than for others. Whereas some of our participants did not mind explaining details about their impairment, others would question why we would need this information. This is delicate, as the type and onset of impairment may impact spatial cognition (see II.2). Our strategy was to explain the need for this information and to reassure users that the information would be kept anonymous.

III.2.2.2 Logistics

Working with impaired users requires adapting rooms and buildings. Henry (2007) gives some recommendations. With regard to the facilities it is important to describe the outline of the room and not to move objects without telling the user. In our user group several participants had a guide dog and it was necessary to provide space to seat the dog during the sessions.

As stated by Lazar et al. (2013) users can arrange their own transport but need to do so in advance. This means that sessions cannot be scheduled spontaneously. Our sessions were planned in advance and took either place in the Institute of the Young Blind in the center of Toulouse or in the IRIT research laboratory on the campus of the University of Toulouse. Both were easily reachable by public transportation and if necessary we guided participants from the metro station to the building. If participants preferred, we provided alternative transportation using the "Mobibus service"[22], a local transportation service for people with special needs. Costs for transportation were reimbursed.

III.2.2.3 End of the Research Study

Participatory design is an iterative process. It is possible to continue development during a long period. However, research projects often have limited resources and will at some point come to an end. Newell and Gregor (2000) have stated that participation in the development of new assistive or design for all technology may raise disappointment among participants. This may be because certain techniques are not successful. In the case where research is successful, disappointment may be even greater as the user who was involved in the project may never personally benefit from the outcome of the research. Indeed, we observed this problem in our design process. From our experience

[22] http://www.tisseomobibus.com/ [last accessed June 14th 2013]

it is important to clearly inform the user about these probable outcomes before getting involved in the experiment. We also feel that this message needs to be repeated during the design process, as users get more and more engaged and motivated for the research project as its design advances.

III.2.3 Analyzing the Context of Use

The participatory design cycle begins with analyzing the context of use. This includes users' characteristics and goals, as well as the technical environment (ISO, 2010). Taking time for understanding users' needs is especially important when working with impaired users for the first time. The analysis of existing research is helpful and necessary. Yet, we cannot emphasize enough that it is very important to actually meet and observe users.

According to Newell and Gregor (2000) users are not very good at explicitly stating their needs concerning a technology which does not yet exist. Their needs can be unconscious and people may not be able or willing to articulate them, or they might come up with solutions that are not optimal. Therefore, methods are needed for facilitating the observation phase. ISO 16982 proposes different methods for analyzing the context including user observation, questionnaires, interviews, or the study of available documents. Petrie and Bevan (2009) present an overview of different accessibility guidelines that can be helpful. However they state several problems with using guidelines. First, they demand substantial effort to learn and apply appropriately; second, the evaluation of a function in a system is time consuming; and third, there may be circumstances where guidelines conflict or do not apply. Zimmermann and Vanderheiden (2007) suggest capturing accessibility requirements through use cases and personas. In the following subsections we present in detail how we implemented the analysis phase in our project.

III.2.3.1 Conclusion from the Literature and User Observations

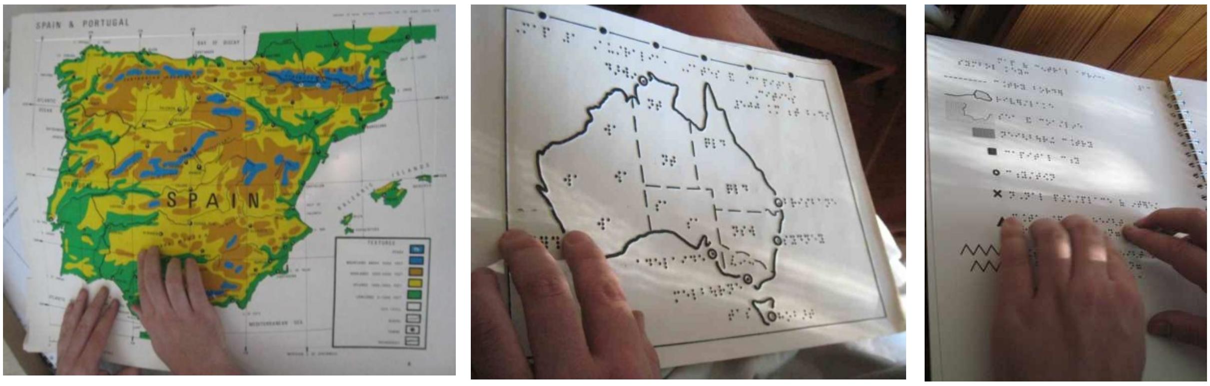
When working with visually impaired users, it is necessary to understand their specific needs arising from the loss of vision. To this end, we did an exhaustive study of literature (see chapter II). This literature research has been accompanied by meetings with visually impaired people and observation of users. Part of these observations have been conducted in previous projects (Brock, Molas, et al., 2010; Brock, 2010a). In this section we aim at underlining how literature and practical observations work together.

In section II.1 we have discussed that visually impaired people can compensate for the absence of vision by making use of the other senses. However, the visual sense is best adapted for certain tasks, such as spatial orientation, and hence the compensation can only be partial. We accompanied a blind user traveling in the city (Brock, 2010a). During this travel, we were wearing a blindfold ourselves and carried a white cane. Even if sighted blindfolded people cannot compensate for the absence of vision as efficiently as visually impaired, it gave an impression on how the other senses are suddenly more actively perceived.

In subsection VI.2.1 we have detailed existing non-visual interaction techniques that can be used for developing interactive maps with visually impaired people. To better understand the general use of assistive technology based on non-visual interaction, we observed the participants, for instance, while using screen readers or electronic travel assistants (Brock, Molas, et al., 2010). These preliminary investigations were necessary to understand that interaction without vision is actually possible.

In section II.2 we have outlined that visually impaired people are capable of creating mental representations of their environment. However, these mental representations differ from those of sighted people. Orientation and mobility therefore present challenges. Several meetings with users allowed us to assess their experiences and challenges regarding mobility. For instance, we followed users travelling on an unknown itinerary in the city center with either a white cane or a guide dog (Brock, 2010a). This allowed us to observe challenges they face during travel (for instance road works that block the side walk, see Figure II.1). We also organized several brainstorming meetings on the subject of orientation and mobility. The aim of these session was to identify challenges, but also information that blind people used as cues for orientation (different types of points of interest that could be perceived with the tactile or auditory sense), and criteria for choosing an itinerary (for instance traffic lights with auditory signals, avoiding large open spaces, etc.). It also helped identifying that guidance during travel is not sufficient. Users stated their need to explore a part of the city with all the information available (landmarks, routes and survey information) before travelling to gain a global understanding of the area.

In subsection II.2.2.5 we showed that maps are a helpful tool for improving the mental representations of an environment. Different concepts of maps for visually impaired people have been presented. Two users in our project collected tactile maps, which allowed us to see the various existing map types. As an example Figure III.2 (a) shows a plastic map produced with vacuum forming. This map contains relief information, and additionally different map elements are colored and text is readable for a sighted person. Thus this map is destined for people with residual vision. In comparison the map in Figure III.2 (b) is produced on swell paper. It is black and white and text is represented as braille abbreviations. This map is accessible for blind people and people with severe visual impairment. A legend as shown in Figure III.2 (c) accompanies braille maps to give more precise information on the abbreviations and textures.



(a) (b) (c)

Figure III.2: Different types of maps for visually impaired people. (a) Colored map for people with residual vision, produced by vacuum forming. (b) Braille map for blind people, produced on swell paper. (c) Legend accompanying a braille map.

In section II.2 we also presented the impact of haptic exploration strategies on the understanding of tactile maps. We observed users while exploring tactile maps (Brock, 2010a). We noticed that all but one user in a group of five people used both hands and several fingers for exploring the map. The person that used only one hand and one finger perceived the map reading as more difficult than the other participants. This is in line with studies on haptic map reading (II.3.2.2.b). However, our observations were of qualitative nature and needed further investigation.

One participant had tried out the ABAplans prototype (see VII.5.5), a map prototype based on raised-line map placed as overlay on a touchscreen with auditory output. He reported very positive feedback on this experience. To study the interest of this concept for visually impaired people, we implemented a simple version of an interactive map (Brock, Molas, et al., 2010). This simple interactive map was limited in precision and functionality but got very positive feedback from our user group. This encouraged us to pursue our idea of developing an interactive map prototype.

Another important aspect that emerged from sessions with our participants was that they did not only want a tool for helping them with orientation and mobility, they also wanted a tool that was comfortable and ludic to use. This notion of "User Experience" is indeed often forgotten when developing assistive technology.

III.2.3.2 Analyzing Interaction for Interactive Maps

Research Question 1 was "What is the design space for interactive maps for visually impaired people? What is the most suitable design choice for interactive maps for visually impaired people?" In section II.4 we replied to the first part of the question by presenting a classification of interactive maps. We showed that the design space for accessible interactive maps is large and heterogeneous. Existing interactive map prototypes vary in different aspects, including the map content, devices and interaction techniques. Several advantages and disadvantages exist for the different types of interactive maps. In this subsection we try to reply to the second part of the question. For this purpose we must first be more precise. It is impossible to identify "the best solution" as this depends on the context, the task, user preferences, etc. Concretely our aim was to develop a prototype that allowed a visually impaired person to explore an unknown geographic area. We did not aim at providing a prototype for mobile interaction, but for exploring a map at home, at school or in another "immobile" context. This exploration would serve for creating a mental representation, for instance concerning the environment around a specific landmark. A first step was therefore to choose the appropriate design for the requirements and user needs in our project. The classification of interactive maps helped us compare different possibilities.

Some existing interactive map prototypes can be used in mobile situations. Typically they are based on smartphones or tablets, because the hardware needs to be battery-powered, lightweight and small. As our aim was not to provide a mobile map, there was no need for the prototype to be built with a mobile device. This enabled us to choose from a larger variety of hardware solutions.

The second question concerned the interactive devices used in the prototype (see II.4.2). Zhao et al. (2008) compared interactive prototypes with different interactive devices. They observed that navigating a map with a keyboard was more difficult for visually impaired users than with a touch screen. Whereas the touchscreen allows users to change position on the map quickly (for instance to "jump" from one side to the other), the keyboard only allows linear exploration of the map (Lazar et al., 2013). Also, the recall of objects in space improved when using a touch screen compared to the same task with a computer mouse (Tan et al., 2002). Accordingly, using a touch screen increased the users' awareness of the external frame of reference and the position of their body compared to that frame (see II.4.4.2 Haptic Reference Frame). Users would then more easily keep track of their position on the map and evaluate relations between different map elements. When using a pointing device (e.g. a force-feedback mouse with a single moving cursor), it is more difficult to keep the reference frame in mind (Rice et al., 2005).

It therefore seems more advantageous to base the prototype design on a touchscreen than on a keyboard or mouse.

The third question concerned the different modalities to use. The ISO standard advises against using tactile output alone (ISO, 2003). Almost all prototypes in the classification possessed some sort of audio output; either speech or non-speech (see II.4.4.1). Some of them have additional haptic feedback which appears to facilitate learning (see II.4.4.2). As an example, adding simple auditory cues to a haptic interface improved the identification of shapes (Golledge et al., 2005). In another study, externalizations of mental representations were more accurate after using a prototype with audio and haptic feedback than after using a prototype with audio feedback alone (Yatani et al., 2012). When comparing use of a touch screen-based system with audio output and with or without raised-line overlay by visually impaired people, users made fewer errors and were quicker when using the interface with the overlay (McGookin et al., 2008). Also they expressed a preference for the overlay interface. Similarly, Weir et al. (2012) observed that users preferred exploring a sonified interactive map application when a raised-line overlay was placed on the touchscreen. Furthermore, tactile and audio modalities have complementary functions when presenting spatial information (Rice et al., 2005). For example, speech output can replace braille text. Representing information through different modalities makes it easier to avoid overloading one modality with too much information. We therefore decided to use both auditory and tactile output modalities.

Finally the question is how to represent information with the tactile modality. Giudice, Palani, Brenner, and Kramer (2012) evaluated a vibro-audio tablet interface against a raised-line drawing for learning non-visual graphical information, both with blind and blindfolded participants. The vibro-audio tablet interface synchronously triggered vibration patterns and auditory information when the users touched an on-screen element. The tactile graphic was embossed and did not offer any additional feedback than the embossed relief. They observed that learning time with the interactive prototype was up to four times longer than with the paper diagram. Giudice et al. (2012) suggested that lines and curves are harder to perceive when indicated by vibrations than when printed in relief. As most blind users have learnt how to explore raised-line maps at school, using an interactive prototype based on a raised-line map relies on their previously acquired skills and is thus probably easier to manage. Furthermore, when using a raised-line map, it is possible to add tactile cues (e.g. outlines of the map) for facilitating users' mental orientation.

Taken together, these research projects show that the combined use of audio and tactile feedback is especially helpful when presenting geographic information. It seems to be easier to use a raised-line map overlay than vibration patterns. The previous studies also show that using a touchscreen may be more appropriate for map exploration than using a mouse or a keyboard. All these arguments led us to the design choice of an interactive map prototype based on a touchscreen, a raised-line map overlay and audio output (see Table III.1).

Table III.1: Summary of the Design Choices

Category	Design Choice
Mobility	Static / at home
Interactive Devices	Multi-touch
Modalities for Interaction	Auditory and Tactile
Representation of haptic modality	Tactile Map Overlay

III.2.3.3 Technical Context: Analysis of Different Multi-touch Display

Studying the technical context is part of the analysis phase. The part of this technical analysis on non-visual interaction is presented in detail in subsection VI.2.1. In the following subsection we present concrete design choices that we have made specifically regarding multi-touch technology.

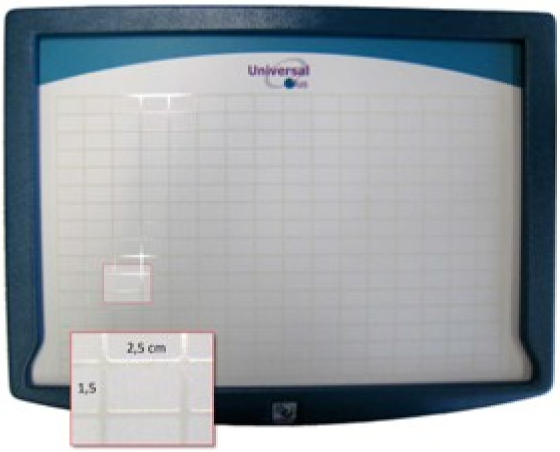


Figure III.3: Geotact tablet by E.O. Guidage. This device offered a 16*16 matrix of rectangular interactive zones, thus providing 256 touchable zones. Reprinted from (Brock, Molas, et al., 2010).

In our first attempt of creating an interactive map during previous projects (Brock, Molas, et al., 2010) we had worked with a "Geotact" tablet of the French company E.O. Guidage[23] (see Figure III.3). This device offered a 16*16 matrix of rectangular interactive

[23] http://eo-guidage.com/ [last accessed June 10th 2013]

zones. The tablet was connected to a computer over a serial port so that each zone could be associated to a sound output file. Obviously the resolution of this technology was very limited as only 256 touch input zones could be differentiated. Feedback from users underlined this problem. It was therefore important to choose a multi-touch screen with higher resolution.

The choice and purchase of a more elaborate multi-touch table was preceded by the comparison of different multi-touch devices. Largillier et al. (2010) proposed a classification of tactile performances for multi-touch panels based on three categories: features (performances related to quantity and richness of tactile information provided by the touch panel), transparency (performances that make the users feel like they interact seamlessly with the user interface) and trustworthiness (measurable performance that impact the confidence a user may have for the touch device). Buxton (2007) proposed distinctions for differentiating multi-touch technology that served as a basis for our analysis. These criteria included for instance size, orientation, precision and the number of inputs. Beyond that, we proposed more precise criteria that are important for designing an interactive map prototype based on a multi-touch display with raised-line map overlay (Brock, Truillet, Oriola, & Jouffrais, 2010). A detailed overview of available technology at the time of the study compared to these criteria is presented in (Brock, 2010b). The following subsections detail these criteria.

III.2.3.3.a Compatibility with Raised-Line Overlays

Touch screens started to be developed in the second half of the 1960s, but have only become popular more recently (Schöning, 2010a). The multi-touch market is now evolving quickly and many different touch technologies exist. Not all of them are compatible with a raised-line map overlay, i.e. some of them do not detect touch input when a paper or other object is placed between the screen and the finger. Compatibility of the hardware with a map overlay was the most important criterion for the choice of multi-touch technology in our project.

In order to find an adapted technology we have made several tests with touch interfaces relying on different technologies. This subsection only details information on touch technology that was available at the time we performed the tests[24] and relevant to the size and type of display we were searching for. It is not meant to be exhaustive.

[24] At the time (spring / summer 2010) the available multi-touch technology was much more limited than nowadays and we therefore did not have much choice concerning technology. As a comparison: the first iPad was released on April 3, 2010. Note also that technology like strain gauge that is used in vending machines but not in consumer displays is not further investigated in this thesis.

Electric Touch Technology

A first main category of this technology is electric touch technology. It comprises capacitive and resistive multi-touch.

Resistive technology (as used in the Stantum SMK-15.4 Multi-Touch display in our previous prototype) is based on two layers of conductive material that are separated by an insulating layer, usually made of tiny silicon dots or simply air (Schöning et al., 2008). When the user touches the screen, the two layers are pressed together and establish an electric current. This current is measured in horizontal and vertical direction to determine the exact touch position. As contact is established by pressure it does not depend on the material of the touching object. A paper overlay thus does not block touch interactions. This type of screen also presents the advantage of low power consumption. On the downside, most resistive displays provide only mono-touch input, are slower than capacitive screens and are also more fragile. As an exception, the Stantum touch display offered multi-touch possibilities.

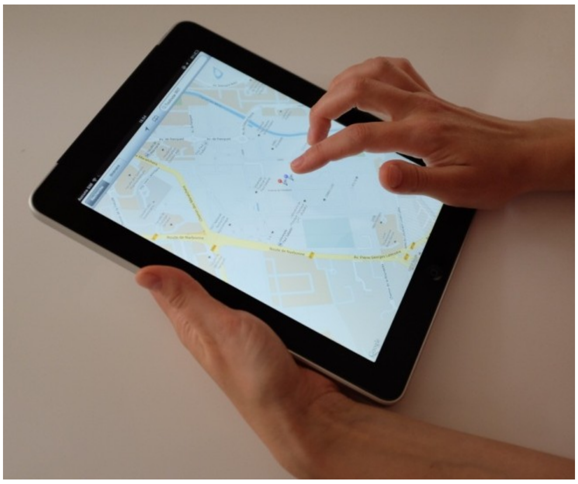


Figure III.4: Photograph of the Apple iPad (first generation).

The second technology is capacitive technology. Johnson (1965) introduced a first capacitive multi-touch screen. Capacitive technology is nowadays used in a lot of commercial products, such as Apple's iPad[25] (see Figure III.4 b). Today, capacitive systems can be differentiated in "surface capacitance" and "projected capacitance" (Schöning et al., 2008). In surface capacitive systems the multi-touch device produces an electrostatic field. The human fingers (or other conductive objects) are also electrical devices capable of storing charge and serving as a conductor. When the screen is touched, charge is transported from the screen to the touching object. The location of touch on the surface can be calculated by the change in capacitance measured from each

[25] http://www.apple.com/ipad/ [last accessed May 22nd 2013]

corner of the screen. This technique, however, has low resolution and does not work with a paper overlay.

In comparison, projected capacitive is based on a grid of two separate, perpendicular layers of conductive material (Rekimoto, 2002). When touched, capacitance forms between the finger and the sensor grid. Touch location can be calculated based on the measured electrical characteristics of the grid layer. Projected capacitive touch technology can detect input at a certain distance from the surface. Therefore the technology works when placing a paper overlay on top. We tested the Apple iPad and the 3M™ Multi-touch Display M2256PW[26] (see Figure III.8). Both systems functioned with a tactile map placed on the surface. On the negative side, projected capacitive technology is more expensive to produce than surface capacitive technology.

A different approach for projected capacitive technology was done with DiamondTouch (Dietz & Leigh, 2001). This technology was composed of a table with integrated antennas transmitting unique signals, a ceiling-mounted projector for projecting onto the table, one conductive chair connected with a receiver per user and a computer. Touching the table completed a capacitive circuit from the transmitter, through the touch point on the surface, through the user to the user's receiver, and back to the transmitter. Most recently Swept Frequency Capacitive Sensing technique has been introduced (Sato, Poupyrev, & Harrison, 2012). Beyond detecting a simple touch event, this technology can also recognize complex configurations of the human hands and body. Different types of objects can be made "touchable". This opens up whole new possibilities for the future.

Optical Touch Technology

A second category of touch technology is optical or camera-based touch technology. This comprises infra-red technology (such as Frustrated Total Internal Reflection or Diffused Illumination), in-plane and out-of-plane optical sensors.

Infra-red technology can be built as a matrix of infrared transceivers (emitters and sensors) around a screen (Schöning et al., 2008). Placing an object (of any material) inside the grid reflects the light. The position is then calculated from this reflection. This technology can turn any screen into a touch screen and can even work as a pure sensor without any display (Moeller, Kerne, & Damaraju, 2011). While using such a technology with a raised-line overlay it must be ensured that the relief is flat and does not interfere with the infrared grid. Unfortunately we did not have any possibility to test this technique

[26] http://bit.ly/M2256PW [last accessed May 22nd 2013]

with the map overlay. Surface Wave Touch Surfaces, is based on a similar principle with ultra-sonic waves instead of infrared rays (Schöning et al., 2008).

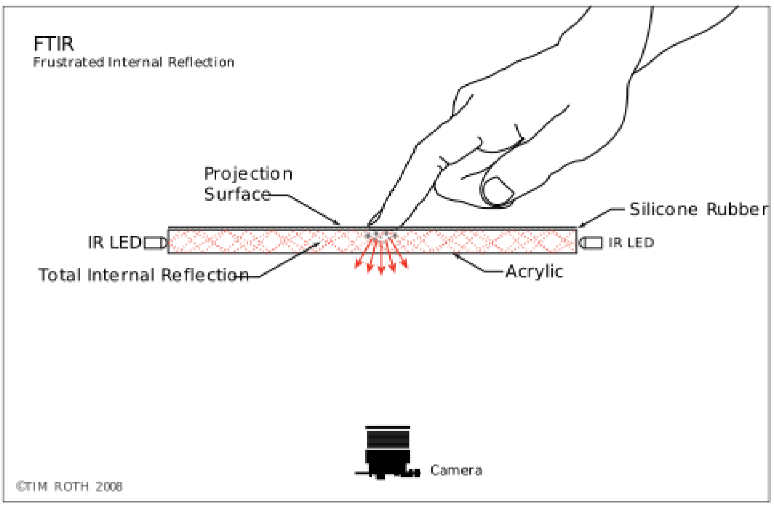


Figure III.5: General setup of a FTIR system by Tim Roth, reprinted from (Schöning et al., 2008) with permission.

Frustrated Total Internal Reflection (FTIR) is another infrared based technology (Han, 2005). Diodes placed on the edge of a Plexiglas plate continuously emit radiation in the infrared range (Figure III.5). The Plexiglas thus acts as a waveguide. Infrared rays are emitted with an angle slightly greater than the critical angle of total reflection. This angle causes the rays to be totally reflected throughout the Plexiglas plate. When the user's finger presses on the plate, light is reflected at the finger's point of contact due to its higher refractive index. Some of the rays deflected by the finger will therefore reach the lower surface of the plate with less than the critical angle, and will therefore be emitted from the plate. These rays form a light spot on the underside of the plate. A special camera located below the device detects these light spots. We have not been able to test the impact of a raised-line overlay on this technology.

Among the infrared technology, there is also Diffused Illumination (Schöning et al., 2008). Unlike FTIR technology, infrared rays are projected onto the touch surface by diodes located below it (see Figure III.6). Thus, the infrared rays are not contained in the surface, but they are projected evenly across the screen. Objects in proximity and objects touching the screen reflect the infrared light and can be perceived by the camera. When the user touches the surface, the contact area prevents propagation of the rays and thus reflects a certain amount of infrared light. An infrared camera located below the surface transmits the video stream to a computer which determines the position with image processing algorithms. We tested the ILight table from Immersion[27] which uses the Diffused Illumination technology. Diffused Illumination can recognize objects other than a finger. It also works with transparent material between the screen and the user. However, a nontransparent paper placed on top of the surface occludes the view for the camera and thus this technology is not adapted for our project.

Figure III.6: Inside of the ILight Table: infrared rays are projected onto the touch surface by ranges of diodes located below it. An infrared camera located below the surface transmits the video stream to a computer which determines the position with image processing algorithms

In-plane technology, for instance the Digital Vision Touch technology as used in the Smart Boards[28], is another optical technology (based on infrared or regular color cameras). Two or more cameras are situated in the corners of the display and observe the touch input. The touch position can be calculated by triangulation. We were able to successfully test this technology with our raised-line map.

In optical "out-of plane" technology, a camera is placed above the surface and filming down to the surface. Touch is detected by tracking the fingers in the video stream. This technology has successfully been used for interacting with raised-line maps in different projects (Kane, Frey, et al., 2013; Krueger & Gilden, 1997; Schneider & Strothotte, 1999; Seisenbacher et al., 2005).

[27] http://ilight-3i.com/en/ [last accessed May 22nd 2013]

[28] http://smarttech.com/ [last accessed May 22nd 2013]

Recently, depth sensing cameras have been introduced such as the Microsoft KINECT[29] or Leap Motion[30]. This technology can be used for touch interaction (Wilson, 2010a). However, at the time we analyzed the multi-touch devices, this technology was not yet commercially available.

Conclusion

Technology that corresponded to our requirement of placing a map overlay on top of the screen included resistive technology (Stantum SMK-15.4 Multi-Touch Device), projected capacitive technology (3M M2256PW and Apple iPad), Digital Vision Touch Technology (SmartTable) and optical out-of-plane technology. As this condition is crucial, in the following sections we limit our analysis to these five devices respectively technologies.

III.2.3.3.b Number of Inputs

The number of touch inputs is part of the "feature" category of the multi-touch hardware (Largillier et al., 2010). Originally most touch devices were mono-touch devices, designed for single points of contacts. Constructing multi-touch sensors is more difficult and expensive than constructing mono-touch devices (Han, 2005). Buxton (2007) differentiated single-finger and multi-finger interaction. Largillier et al. (2010) further classify multi-finger interaction in dual-touch, limited multi-touch and unlimited multi-touch. Furthermore, Buxton (2007) distinguishes between multi-hand interaction, i.e. different hands working on the same or different devices, and multi-finger interaction, i.e. different fingers from the same hand interacting. Finally, there is also an important distinction between multi-touch and multi-person. It makes a difference if touch inputs originate from two fingers of one user's hand or from fingers from two different users. Two different users will effect separate interactions, whereas two inputs from one user might be taken together to one interaction technique (for instance pinch gesture).

For our project we did not need multi-person interaction. Yet, we considered it important that a tactile device offered multi-finger and multi-hand characteristics. In the best case we wanted it to react to at least 10 inputs in parallel for two reasons. First, visually impaired people usually explore tactile maps with both hands and multiple fingers (Wijntjes, van Lienen, Verstijnen, & Kappers, 2008b). Designing accessible and usable interaction for map exploration might therefore demand more than one touch input. Second, a multi-touch table with at least 10 touch inputs also permits to track and register finger movements during map exploration.

[29] http://www.xbox.com/en-US/kinect [last accessed May 23rd 2013]

[30] https://www.leapmotion.com/ [last accessed May 23rd 2013]

From the touch displays that have been successfully evaluated for compatibility with the paper map overlay, the 3M M2256PW offered multi-finger interaction for up to 20 cursors. Similarly, the Stantum device and the Apple iPad provided real multi-finger input. Beyond that, the SmartBoard even provided multi-user capacities. For the out of plane technology, the number of tracked fingers depends on the implementation. It is possible to implement recognition of multiple touch inputs.

III.2.3.3.c Screen Size

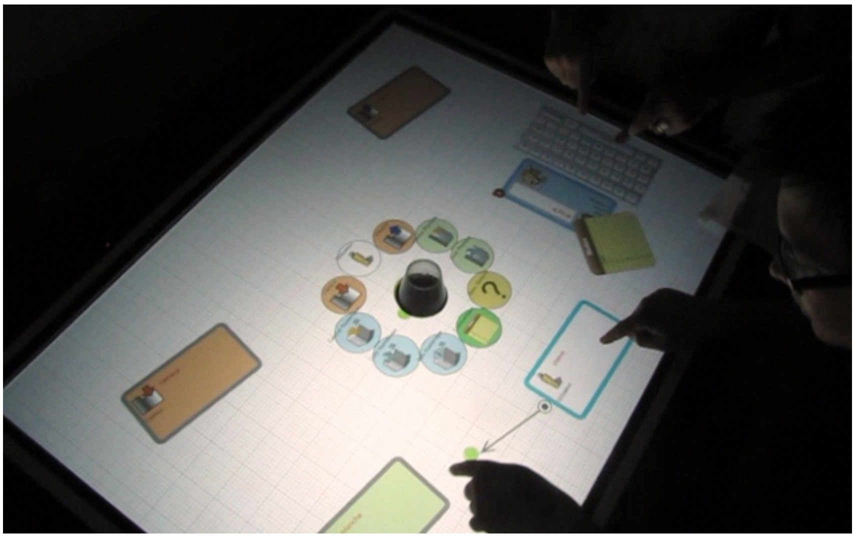


Figure III.7: Users working collaboratively on a large touch table. Reprinted with permission from (Bortolaso, 2012).

As has been stated by Buxton (2007), the size of a multi-touch display is important. Size largely determines what muscle groups are used for interaction. It also determines how many hands (of one or several users) and how many fingers can be active on the surface. The types of gestures that are suited for the device depend on its size. Finally, the adapted size depends on the kind of information that is to be displayed on the screen. Tatham (1991) proposed that maps for visually impaired people should not exceed a certain size (two hand spans, 450 mm). This size permits to use one of the fingers as anchor point to put other map elements in relation to this one (regarding distance and direction for instance). In what concerns memorization of spatial knowledge, it can be more challenging to use large scale touch tables, as those used for instance in collaborative multi-touch applications. On the other hand it is also difficult to present tactile maps in a very small format—e.g., size of a smartphone screen—as there is little space to present all map details. In previous projects (Brock, Molas, et al., 2010) we observed that the size of maps should be at least A4 format, but users preferred maps in A3 format. We therefore concluded that the size of the Ipad was too small for our map project, whereas the size of the SmartTable was too large. The sizes of the 3M Display and the Stantum display were well adapted. The size of the map for out of plane technology depended on the implementation.

III.2.3.3.d Accuracy

To associate sound output to map elements, it must be possible to identify the exact position of a finger. As presented by Power (2006), inaccuracy of finger position can lead to errors in the sound output of interactive maps. Largillier et al. (2010) differentiated between pointing accuracy—the precision of a stationary contact—as well as tracking precision—the precision of a path following a moving finger. They stated that reaching pixel resolution with an average user's fingertip was utopist. We propose that pointing precision should be better than the size of one finger. Tracking accuracy not only depends on spatial resolution but also interpolation method and acquisition rate (Largillier et al., 2010). A slow technology (scanning rate at 40 to 60 Hz) will fail to deliver accurate tracking of fast movements. They also observed that the precision varied depending on the position on the screen surface. Finally the precision indicated in the technical datasheets of a screen did not always correspond to the actual precision. For the 3M M2256PW a precision of 0.28 mm was indicated. The tactile precision of the Stantum SMK-15.4 Multi-Touch Device was indicated as <0.5 mm. Both resolutions proved sufficient during our pretests. We were unable to find any information on the precision of the SmartTable and the IPad. The precision of out-of-plane technology depends on the camera used as well as the hardware setup (positioning of the camera, etc.).

III.2.3.3.e Orientation

As stated by Buxton (2007) orientation of a multi-touch device—vertical versus horizontal—is important. On a horizontal display users might rest their hands on the surface during exploration. In different sources this situation is called, unintentional, accidental or unintended multi-touch input, i.e. hand or finger movements that do not convey meaningful information (Pavlovic et al., 1997). This can lead to confusing situations in which the user does not understand what is causing the output interaction. If the number of touch inputs is limited, accidental touch input can even block the system from recognizing the intended touch interaction from users' fingers. Vertical surfaces do not cause this problem. However, physical fatigue may be a problem in these systems as users are forced to hold their arms in front of them for interaction. Another factor to take into consideration is the application type. Visually impaired users normally explore raised-line maps on a horizontal surface rather than fixed to a wall[31]. To be as close as

[31] Exceptions are raised-line maps in public spaces, public transportation or touristic sights that are often fixed to walls of buildings in vertical position.

possible to their habitual tools, we decided to set our map in a horizontal plane. All of the devices that we investigated present this possibility.

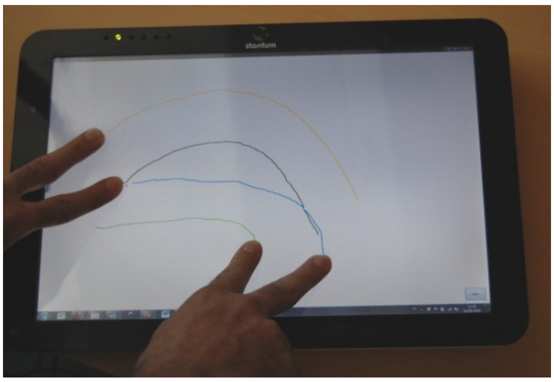
III.2.3.3.f Summary

Table III.2 shows a summary of the evaluation of selected multi-touch devices according to the criteria that have been described above in detail. Based on this comparison, we chose the Stantum SMK-15.4 Multi-Touch Device and the 3M Multi-touch Display M2256PW as possible solutions.

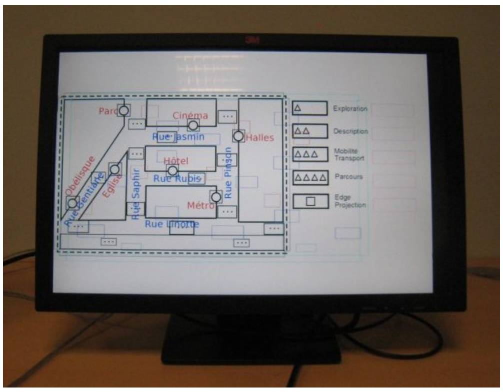
Table III.2: Evaluation of selected multi-touch devices according to different criteria.

Display Type	Compatibility with Overlay	Number of Inputs	Size	Tactile precision	Orientation	Purchasability
Stantum SMK-15.4	Yes	10+	Adapted	< 0.5 mm	horizontal	No
Apple IPad	Yes	2	Too small	?	horizontal or vertical	Yes
3M M2256PW	Yes	20	Adapted	0.28 mm	horizontal or vertical	Yes
Smart Table	Yes	Multiple	Too Large	?	horizontal	Yes
Out of Plane	Yes	Depending on implementation	Adapted (depending on implementation)	Depending on implementation	horizontal or vertical	Yes

The Stantum display has a physical dimension of 20.5 * 33 cm. The default display resolution is 1280*800. It provided real multi-touch functionality, i.e. recognition of more than one touch input (see Figure III.8). The 3M Multi-touch Display M2256PW is a 22 inch display and has a 1680 * 1050 resolution. It recognizes 20 simultaneous touch inputs. It is specified for less than 6 ms response time and it has a touch precision of 0.28 mm. Orientation can be fixed in horizontal and vertical position.



(a)



(b)

Figure III.8: Photograph of different multi-touch devices. (a) The Stantum SMK-15.4 Multi-Touch Display. (b) The 3M™ Multi-touch Display M2256PW.

III.2.4 Generating Ideas

In a second phase of the participatory design process, it is useful to apply methods of creativity, such as brainstorming (ISO, 2002), in order to generate ideas for solutions. Generating ideas is challenging as users might come up with solutions that are not optimal, or they might even not know how to solve their needs (Newell & Gregor, 2000). We proposed that the Wizard of Oz technique—even though it is a low level prototype and thus already part of the next design phase—could be used for stimulating creativity.

III.2.4.1 Brainstorming

There are variations and more specialized methods such as the "Group Elicitation Method" (Boy, 1997) which proposes "brainwriting"—a written variant of brainstorming. However, these methods are not usable with visually impaired people because the methods of sharing ideas are often based on vision. The dependence on vision concerns two aspects: the content that is created and exchanged as well as non-verbal communication between participants (Pölzer, Schnelle-Walka, Pöll, Heumader, & Miesenberger, 2013).

Regarding the first aspect; when brainstorming with sighted people, all ideas created during the session are written down on paper or a whiteboard. This allows participants to access ideas at any time. It facilitates group dynamics as the sharing, selection and structuring of ideas. The methods of visual notation used in brainstorming also structure information spatially and organize it on multidimensional criteria (groups, connections, graphics tags). Very little work has been done yet to provide access to content for visually impaired people. Most recently Pölzer et al.(2013) proposed a tool for sharing mind maps between visually impaired and sighted users. This tool uses different input and output devices, such as multi-touch table, camera-based gesture recognition and a braille display. The mind map is made accessible by means of the braille display and a screen reader connected to the multi-touch device. However, during the time of our studies this tool was not yet available. Therefore in our study a sighted facilitator was in charge of making the content accessible.

Concerning the second aspect; in a group of sighted people, participants communicate with each other through non-verbal exchanges (looks, gestures). In a conversation, the semantics of verbal discourse relies heavily on the facial expression and gestures of the speaker. Gestures also have a role in speaking and changing turns between speakers, especially when the group is large. Intentions of speaking are announced through these non-verbal exchanges and turn between speakers is managed quickly and automatically. For brainstorming, fast throughput supports dynamic response and originality of ideas. The facilitator focuses on the overall approach and time management. Blind people lose all these gestural information and are forced to request information about the intentions of interlocutors. To manage a brainstorming session with blind people, the facilitator must manage much more imperatively the turn taking between speakers. He should guide and mediate the communication of the group by distributing speech, so to avoid silence and simultaneous speech. Also, he can verbalize if he perceives intentions of turn taking (for instance "I think Jean wants to say something").

Figure III.9: Brainstorming session with visually impaired users. A user is taking notes with a BrailleNote device. Reprinted from (Brock, 2010a).

We carried out brainstorming sessions during preceding projects (Brock, Molas, et al., 2010; Brock, 2010a). The participants in these sessions were five blind people from the Institute of the Young Blind, one sighted locomotion trainer, one blind researcher and five sighted researchers. During our sessions, a sighted researcher wrote down the ideas and accompanied it by oral feedback. To enable participants to better share ideas, we regularly read out the list during the session. However, there is a big difference between a visual list and a spoken list. Vision is "constant" and freely accessible to all, whereas verbal repetition of this list gives access at one point in time. Participants make cognitive effort to memorize the spoken list. This can be especially challenging for sighted participants that are not used to this setup. To facilitate the memorization we restructured ideas not by chronological order but by themes. In a second phase of the brainstorming, we asked the group to structure ideas collectively and prioritized the most relevant information. We read the items one by one and assigned a priority index after collective discussion. These ideas formed the basis for the creation of a list of features ordered by priority. They were then transformed in three design scenarios. Participants were divided into three groups with two blind and two sighted people in each group. Each group wrote a screenplay based on the generated ideas. Notes were taken by sighted participants while one blind person took notes using a BrailleNote[32] portable device (see Figure III.9). Finally, each scenario was presented to the whole group.

III.2.4.2 Stimulating Ideas: Accessible Wizard of Oz

Creating ideas can be difficult for users if the concept is very new for them. Although many visually impaired users have been exposed to technology, the idea of interactive maps does not always inspire them. Therefore we proposed to use the "Wizard of Oz" method for stimulating users' ideas.

The "Wizard of Oz" method aims to evaluate a system by simulating some or all of the functionalities of a prototype, while users believe that they are interacting with the real system (Kelley, 1984). Often the visual display is simulated and thus the method is inaccessible to visually impaired people. Therefore, an adaptation of this method is required for working with visually impaired people. It is possible to adapt it using non-visual, i.e. mainly auditory or tactile modalities. Klemmer et al. (2000) offer a Wizard of Oz software to facilitate the simulation for the design of voice interfaces. Their software is designed for systems using auditory modality for input and output. Serrano and Nigay (2009) proposed "Open Wizard", a Wizard of Oz software for multimodal systems. It simulates the input but does not simulate output modalities. Only recently, studies on the "Wizard of Oz" method directly addressed visually impaired people. Miao, Köhlmann, Schiewe, and Weber (2009) proposed the use of tactile paper prototypes for evaluating their design with visually impaired people. Their envisioned system was a display with raised pins, thus having both tactile input and output.

We recommend choosing modalities in the Wizard of Oz simulation that correspond to the interaction modalities in the final prototype, in order to guarantee consistency between the simulation and the prototype. As a result we had to create our own Wizard of Oz simulation that corresponded to our needs. In contrary to the system of Miao et al. (2009), the concept of our map prototype is based on tactile and auditory cues. In order to use coherent input and output modalities, we chose to adapt their method by using real raised-line maps (see subsection III.2.5.1) and simulated speech output (Brock, 2010a).

We used the Wizard of Oz method for a low-fidelity evaluation of our system and at the same time for creating ideas. We had two objectives for the Wizard of Oz Session: 1) to test if the concept of an interactive map prototype was usable and enjoyable for the visually impaired users, 2) to stimulate the creativity of participants.

[32] http://www.humanware.com/en-usa/products/blindness/braillenotes [last accessed August 22nd 2013]

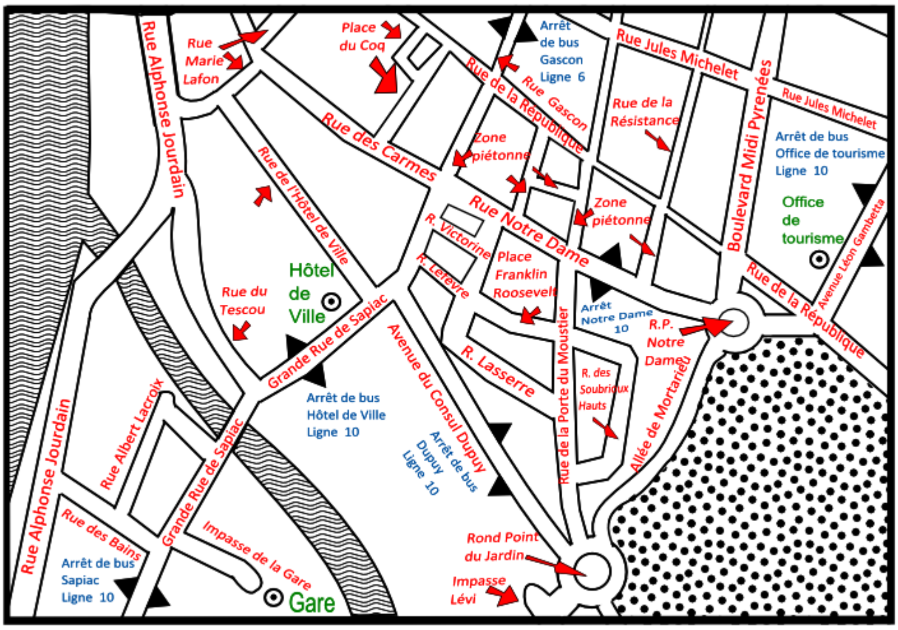


Figure III.10: Experimenters instructions for the simulated speech output (in French).

We organized informal Wizard of Oz sessions with four users. The map used in this evaluation is presented in subsection III.2.5.1. A visual map containing names of map elements in French was prepared to help the experimenter (Figure III.10). Users were invited to individual sessions. Participants were chosen among those we had met in previous brainstorming sessions according to three criteria: 1) their interest in map exploration, 2) creativity during previous sessions and 3) never having explored an interactive map. As none of the users was familiar with the Wizard of Oz method, users were first introduced to the methodology. Then, they were asked to freely explore the tactile map (Figure III.11). When users required audio information, they touched specific positions on the map. The experimenter then read out the name of the map element as indicated on the map instructions (Figure III.10). The map contained specific "interactive" symbols for public transportation and points of interest. All other elements (streets, parks, rivers) were not located with specific markers. They were simulated as "entirely interactive". Users were encouraged to express any comments or errors during map exploration.

The duration of sessions varied between 1h and 2h15min. Users expressed positive feedback on the concept of an interactive map. For what concerns ideas for future prototypes, several users stated that they would appreciate having several levels of information (for example street names only, public transports only, shops and points of interest) and the possibility to switch between them. In general, public transportation seemed to be of great importance to users as well as distance. Also, they desired description on crossing intersections and roundabouts. We observed that users tried to interact with the experimenter by asking questions during map exploration and did not stick to the Wizard of Oz protocol. This might be because the method was new to the users or because the experimenter did not impose the formal character of the session. Nevertheless, the sessions have been very productive in terms of useful feedback and creation of ideas.

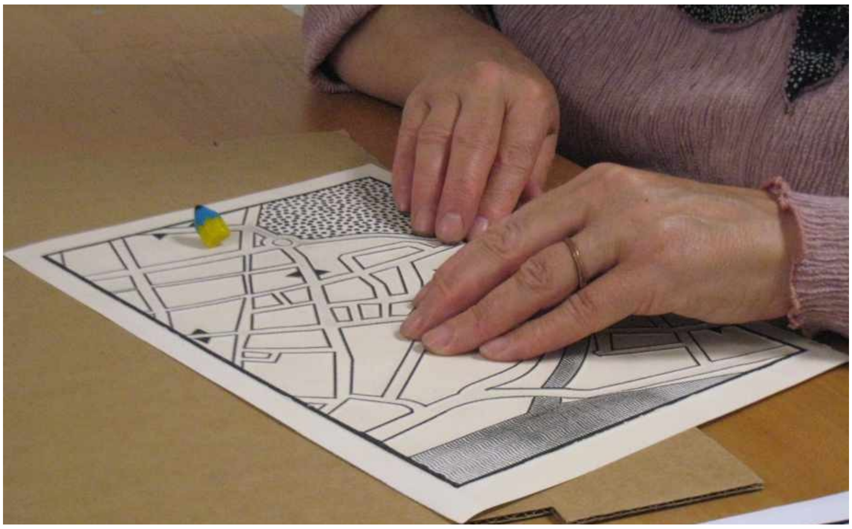


Figure III.11: Wizard of Oz Session. A visually impaired user is exploring a tactile map while the speech output is simulated.

III.2.5 Prototyping

Prototypes should be based on the ideas generated collectively in the previous step. Prototyping can be done with low- and high-fidelity prototypes. Prototypes allow users to evaluate, validate or refute concepts or interactions, and to select or propose new ideas. To produce these prototypes there is a choice of several methods. Again, these methods are often based on the use of visual content. For instance, Rettig (1994) and Snyder (2003) demonstrate the use of paper prototyping, in which drawings or collages serve as low-fidelity prototypes. The same visual constraint exists for the use of video prototyping (Mackay & Fayard, 1999).

An alternative to paper prototyping is coding low-fidelity prototypes. According to Sefelin, Tscheligi, and Giller (2003) the results achieved with these prototypes are equivalent to those obtained with paper prototypes. In addition, interviews conducted at the end of tests comparing paper mock-ups and software prototypes revealed that 22 of 24 participants preferred working with software prototypes. New software such as Adobe Flash or Silverlight MS facilitates the creation of low-fidelity prototypes. However, these technologies cannot be used with blind users because the produced models are not accessible using screen readers.

As a consequence we propose an iterative approach for developing interactive prototypes. Several design steps were necessary for developing a high-fidelity prototype. We aimed at developing a prototype with two objectives. First, our goal was to develop a prototype that could be used in a usability study (see chapter IV). Second, we aimed at a prototype that could be used to further develop new interaction techniques for non-visual map exploration. Both purposes lead to two different systems that are both based on the same functional prototype.

In the following subsections we detail the design of different system components. These components include the tactile maps, software architecture and interaction techniques

III.2.5.1 Designing Tactile Maps

A first step in the design of the interactive map prototype was the design of the raised-line maps (see section II.3.3 for the theoretical background on tactile maps). As there is no standard for designing raised-line maps, we first had to to explore different methods for representing geographic information in raised-line maps. In the first two cycles, we wanted to observe how users reacted to these different ways of representing information. Our long-term goal was to provide a readable map that could serve as a platform for experimentation.

Among the different production methods (II.3.3.1), we chose microcapsule paper because it is the easiest technique. Another important aspect was that this kind of paper is slimmer, which is advantageous to detect touch input on the touch table through the paper map. Finally, Picard and Lebaz (2012) revealed a high accuracy for recognizing raised-line images on microcapsule paper. During all design stages, we used A3 and A4 format swell paper of the brand ZY®-TEX2. A3 maps were printed in landscape format with a Toshiba e-STUDIO 355 copier. A4 drawings were printed in portrait format with a Dell 3330dn Laser Printer XL. In both cases we used the same Piaf fuser for creating the raised-lines. Our raised-line maps respected different guidelines for tactile map drawings (Edman, 1992; Tatham, 1991). More precisely they were based on previous work on a visual-tactile atlas for visually impaired people (Picard, 2012).

Maps were designed with the Open Source Inkscape software[33] in SVG (Scalable Vector Graphics) format. SVG is convenient to provide both a topographic view of a geographical place and a textual description (based on XML[34]) of the included elements.

33 http://inkscape.org/ [last accessed May 14th 2013]

34 http://www.w3.org/XML/ [last accessed June 7th 2013]

Therefore, many projects use the SVG format for the design of interactive maps (Campin et al., 2003; Daunys & Lauruska, 2009; Miele et al., 2006; Tornil & Baptiste-Jessel, 2004; Wang et al., 2009). The SVG format allowed us design maps with an image editor and to print a raised-line map from this topological view, but also to add labels to map elements in the textual view. As the visual view is vector-based, it can be displayed at various output resolutions (Tornil & Baptiste-Jessel, 2004). Furthermore, it the textual view can be parsed easily by a computer program. Another advantage of SVG is that it can be easily created from existing Geographic Information Systems. For instance OpenStreetMap provides the possibility to export SVG files.

III.2.5.1.a First Map Drawing

Figure III.12: Map drawing used in the Wizard of Oz sessions. The different "interactive" geographic elements are highlighted. Points of interest are represented by circle symbols, bus stops by triangles, parks and rivers by different textures. Reprinted from (Brock, 2010a).

The objective of this design step was to design a first map and to evaluate how readable the chosen representation was for the visually impaired users (Brock, 2010a). We chose to display non-familiar content as we wanted to observe whether users could understand an unknown city area based on the map drawing. We based the on the outlines of the city center of Montauban, France (Figure III.12). We used a visual map extracted from OpenStreetMap as a model to draw the outlines of roads and buildings. However we slightly altered the content so that it included different elements such as roundabouts, parks and public transportation. The objective was to test different tactile symbols for representing various elements. This map design was then used in Wizard of Oz sessions (see subsection III.2.4.2). Users found some ambiguities concerning the representation of the map. For instance, all users found it difficult to distinguish between streets and open places. This information was however important for them. Also users confused the streets and the exterior outline of the map. These findings were taken into account to improve the map layout for the next version of the raised-line map.

III.2.5.1.b Second Map Drawing

In this step we aimed at improving our map design by taking into account the feedback of the previous evaluations. We therefore adapted the map based on the feedback from the previous evaluation. As in the previous tests users had mixed up the outline of the map with streets, we removed it. We added an arrow and braille text to indicate North direction. We also added the representation of railway tracks as dashed lines in order to test whether participants could distinguish dashed lines from continuous lines. Feedback from the previous explorations also showed that all participants had problems distinguishing streets from open spaces. To remedy this we represented buildings in black (thus as raised elements) and open spaces in white (thus as flat elements) as shown in Figure III.13. This also had consequences on the representations of points of interest (POI) and public transportation. We chose to represent POIs as white circles inside black buildings—i.e. flat circle inside a relief surface. Public transport was represented as a black triangle inside a white square as proposed by Wang et al. (2009). Only during the map production process, we noticed that printing a tactile drawing with lots of black elements was actually complicated. During the printing the ink did not dry quickly enough on the paper, therefore leaving ink traces on white spaces. During the heating process, the black areas heated too much, which resulted in blisters on the black map elements. We therefore drew the conclusion, that a raised-line image produced on swell paper should not contain too many black elements for technical reasons alone. This is in line with the findings reported by Edman (1992).

Figure III.13: Map drawing used for the second interactive map prototype. Buildings were represented as black elements, whereas open spaces were represented in white.

In this step, we decided to work on the area around the Institute of the Young Blind which was familiar to users. The objective was to see if the represented map corresponded to the participants' mental representations. As people were familiar with this area, they wanted the map content to be as close to reality as possible. However, this was a difficult task as the area has some very small streets, green areas and rivers that are hard to represent without making the map cluttered. It was therefore sometimes necessary to alter the representation of distances, sizes and directions in order to fit in all required map content (Tatham, 1991). We chose a compromise between realistic representation and readability. Another challenge consisted in the fact that a lot of the pedestrian zones were not represented in the Geographic Information Systems that we used as a basis[35] (Kammoun et al., 2010). This required additional manual modifications to the map. This design step made us understand that designing realistic maps that can be used as real orientation aid is very challenging. As our aim at long-term was the design of an experimental map, we did not further investigate how these design steps could be improved.

Three blind users explored the map and reported problems. Only one user preferred the map with black elements for buildings. They also found that the map was cluttered as we had tried to represent all the small parks and rivers at a high zoom level. As a consequence, in the following maps, we abandoned the idea of drawing buildings as black elements and we concentrated on the representation of a less complex environment for experimental purposes.

III.2.5.1.c Third Map Drawing

For our experimental prototype we produced a simplified tactile map without the objective of presenting a realistic environment. It is described in detail in the material section of the following chapter, subsection IV.2.1.1.

III.2.5.2 Designing Software Architecture

We studied two different types of software architecture for our prototypes. First, we investigated a modular software architecture. In this architecture different modules, i.e. applications, were connected via a software bus. The aim of this highly flexible architecture was to facilitate rapid prototyping. In a second step, we analyzed existing gestural application programming interfaces (API) for a more high fidelity prototype.

[35] We checked map content for Google maps and OpenStreetMap. By the time, OpenStreetMap contained more pedestrian information than Google Maps. Since then, efforts have been undertaken for both Geographic Information Systems to include further pedestrian information.

III.2.5.2.a Modular Software Architecture

The aim of this design step was the development of a bus-based modular software architecture. The concept of bus-based communication can be found in the literature in gesture APIs (Kammer, Keck, Freitag, & Wacker, 2010). Wagner (2010) also used a modular architecture in his interactive map prototype for visually impaired people. The main advantage of such architecture is its versatility as it allows removing, replacing or adding modules. For example, it is easy to change the touch screen and corresponding driver without having to adapt the rest of the applications. Therefore it facilitates prototyping as means of the participatory design process. Furthermore, it can be possible to integrate modules coded in different programming languages. This can be convenient, as different parts of the application (for instance touch input and speech output drivers) can be easier to code in specific programming languages.

The Ivy Software Bus

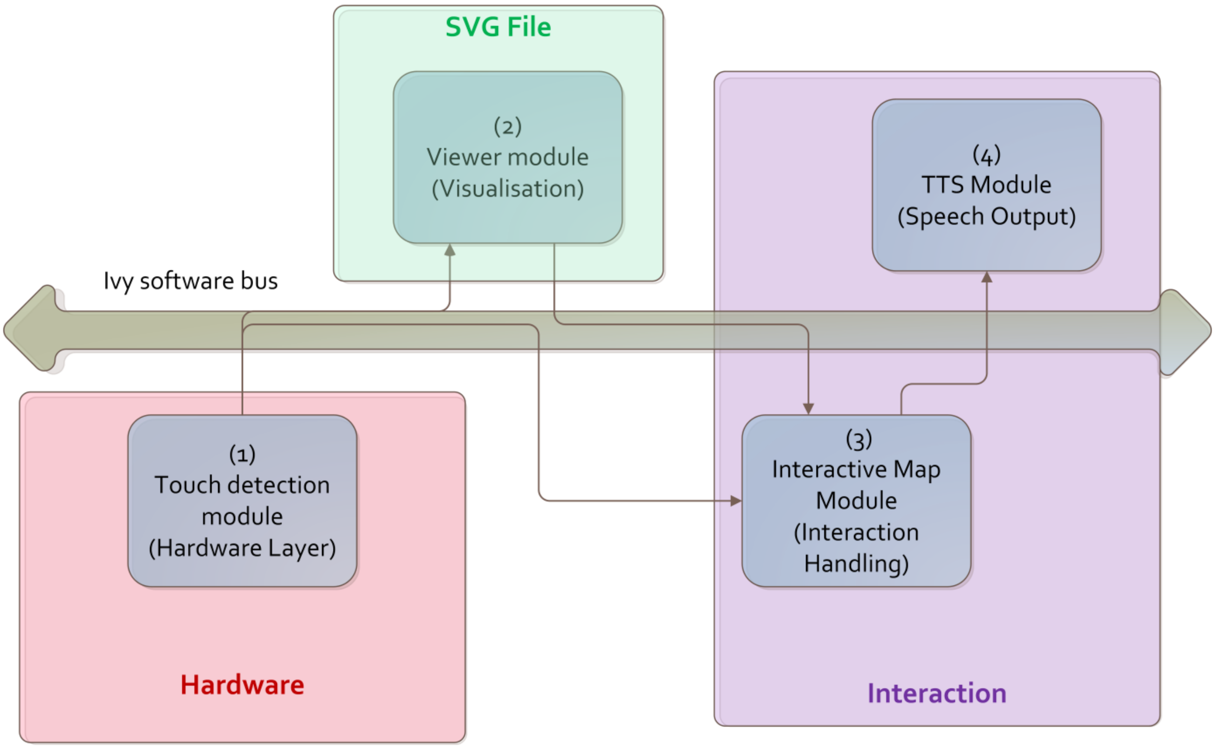


Figure III.14: Message-based software architecture. Four different modules exchange messages using the ivy software bus.

We chose to use the ivy middleware to connect different software modules (Buisson et al., 2002). This software bus corresponded perfectly to our needs as it provides an easy means for prototyping applications. It allows connecting heterogeneous modules—i.e., implemented in different programming languages, using different hardware or even running on different machines connected via network. Ivy provides libraries for different programming languages, such as Java, C++ or Python, so that applications can easily implement ivy connection. The software bus works with a text-based message system. Software agents send these text messages to the bus and each agent specifies which type of message it wants to receive. For implementing an Ivy-based application it is therefore necessary to define precise regular expressions for the different messages (see appendix VII.1).

Our prototype was based on four different modules: a touch detection module, a viewer module, the interactive map module and the TTS (text-to-speech module). Figure III.14 shows the architecture of our prototype.

Touch Detection Module

The objective of this module was detection of touch input. The implementation varied depending on the multi-touch screen and is detailed in subsection III.2.5.4 for each prototype specifically.

Viewer Module

The objective of this module was to display the map information as well as to determine which map element has been picked via the specified touch interaction. We used the "SVG Viewer", a module that had been developed in our research team beforehand[36], which provided an interface to the Ivy bus. Using the touch position it determined the element within a SVG[37] drawing that had been touched. It then sent a message with the element's ID on the Ivy bus. The SVG Viewer has been coded in Java.

For exchanging information on map elements between the different modules, labels were associated to map elements in the SVG files. We specified labels for the following map elements: roads, parks, parking lots, buildings, POIs (points of interest), rivers, squares, crossings, bridges, public transport and railways. Each label was completed by a unique number for each map element.

Interactive Map Module

A third module—coded in Java—contained the principal algorithm of the interactive map: the state machine for touch interaction. This module received messages from both previously described modules. Using the labels and numbers from the Viewer module it associated touch events with the picked map element. Finally, it sent the speech output to the TTS module. For this it used a lookup-table based on labels and numeration for each map element that indicated a string for the TTS output.

[36] The author of the "SVG Viewer" is Mathieu Raynal.

[37] http://www.w3.org/Graphics/SVG/ [last accessed May 14^{th} 2013]

TTS Module (Text-to-speech)

We chose to use a TTS rather than recorded speech, because synthesized speech is more flexible (see II.4.4.1.a). The TTS module received a message containing a string from the interactive map and converted the string to speech output. It was coded in C++ and based on Microsoft Speech Application Programming Interface version 4. It was connected to Ivy by using the PPilot module, an Ivy module for Text-to-Speech Conversion[38]. We used this module with different TTS versions.

Ivy Message Protocol

As described above, using Ivy with different modules demands a precise communication protocol. For the current prototype we defined different messages. The message protocol can be found in the appendix (VII.1).

III.2.5.2.b Analysis of Different Gestural APIs

The above described modular software architecture served for the rapid development of a low fidelity prototype. In a next step, we aimed at choosing an adapted API (application programming interface) for implementing gestural interaction. We identified different crucial criteria for this choice:

- The API had to be compatible with the 3M Projected Capacitive M2256PW touch screen for the proper functioning of the application.
- The API should provide some basic gestures and the possibility to develop new ones.
- The API needed to handle true multi-touch with input of at least 10 fingers.
- We wanted to code with a programming language that we already mastered and in a Microsoft Windows environment.
- Finally all the known problems with the APIs should be identified and discussed.

Kammer et al. (2010) present a taxonomy of different multi-touch APIs. They analyzed nine APIs following several criteria: platform independence, software architecture, possibility of using tangible objects, type of information on touch events, predefined standard gestures, gesture extensibility and visualization support. Not all of these criteria applied to our application, for instance tangible interaction was not of interest for us. Among these nine APIs, we further investigated four of them that sounded

38 PPilot has been developed by Philippe Truillet and is available at: http://www.irit.fr/~Philippe.Truillet/ztp/ [last accessed May 2013]

most promising: Multi-touch for Java (MT4J, Laufs, Ruff, & Weisbecker, 2010), Sparsh UI (Ramanahally, Gilbert, Niedzielski, Velazquez, & Anagnost, 2009), Gesture Works39 and WPF- Breeze40. Table III.3 summarizes the comparison of these APIs. All of them function under different operation systems, are compatible with different multi-touch screens and provide real multi-touch capacities as long as the multi-touch hardware does. These criteria did therefore not influence our choice. All but Breeze provided possibility for defining own gestures. Finally, we opted for MT4J as it was distributed under a free license, Java programming language seemed a good choice, and most importantly as it had the greatest variety of predefined gestures.

Table III.3: Comparison of different multi-touch APIs based on the criteria for our map application.

	MT4J	Sparsh UI	Gesture Works	Breeze
Operation System	Windows 7, XP, Vista, Ubuntu Linux & Mac OSX	Windows, Linux	Windows 7, XP, Vista & Max OSX 10.6	Windows 7, .NET 4.0
Programming Language	Java	Java / C++	Adobe Flash & Flex	C#
Compatible Multi-touch screens	All	All	All	All
Predefined Gestures	Tap, Double Tap, Drag, Rotation, Resize, Zoom, Move (2 fingers), Lasso	Tap, Drag, Zoom, Rotation	Click, Zoom, Drag, Rotation	Click, Zoom, Drag, Rotation
Create own gestures	Yes	Yes	Yes	No
Real multi-touch	Depending on Hardware	Depending on Hardware	Depending on Hardware	Depending on Hardware
Known problems	None	Demands a gesture handling server and a multi-touch simulator	No free licence	None

[39] http://gestureworks.com/ [last accessed June 6th 2013]

[40] http://code.google.com/p/breezemultitouch/ [last accessed June 6th 2013]

III.2.5.3 Designing Interaction Techniques

The iterative design approach allowed us to experiment different interaction techniques, concerning input as well as output. We were inspired by the analysis of non-visual interaction in interactive maps for visually impaired people (VI.2.1).

III.2.5.3.a Touch input

Touch interaction is a powerful means of interacting (see II.4.3.2.a). In a first step we aimed at very simple interaction. The objective of the interaction was to distinguish exploratory finger movements (i.e., touching the screen for following the raised-lines on the map) from touch interaction (i.e., pressing the screen with the aim to obtain information). In a first version we implemented a single tap interaction.

Pretests of the prototype with three blind users clearly proved why it is always important to test prototypes with the specific user group as demanded by the ISO 9241-210 standard (ISO, 2010). Although the single tap worked fine with sighted users, it did not work with blind users. We observed that, visually impaired users explore tactile maps with several fingers (Brock, 2010a). When multiple fingers were simultaneously applied on the display, many sound outputs were produced. In addition, for most visually impaired people, one or several fingers serve as reference points and stay in fixed positions. Although the touch surface was supposed to produce only touch input events when a finger touched a surface for the first time, sometimes it also produced touch input for a resting finger. We suppose that the touch surface was sensitive to tiny movements of the resting finger. The blind users who tested the system were then not able to understand which finger caused sound outputs. Similarly, McGookin et al. (2008) observed accidental speech output for single tap interaction. We could suppress some of these messages by implementing a state machine that hindered repetition of the same messages within a 5 second interval. Yet, the messages resulting from the use of multiple fingers remained a problem.

Two possibilities existed for handling this situation. First, it would have been possible to adapt the user to the interface by forcing users to rely on a single finger while exploring the map. However, as we wanted map exploration to be as natural as possible, we discarded this possibility. The second possibility was to adapt interaction to user behavior. In this regard we had several ideas on adapting interaction techniques. First the current map prototype was interactive on the whole map area. Limiting the interaction to smaller zones would decrease the risk of multiple interactions. However, as the user could always by chance touch several marks at the same time, this step alone was not the optimal solution. Second, measuring the pressure of the touch input could allow differentiating exploratory movements from touch input. However, most touch devices do not indicate the force of input pressure. As a third possibility we imagined introducing a button on the map. For activating speech output the user then had to tap with one finger on the button and with a second finger on the map requested element (Brock, 2010a). However, this type of interaction interrupted the natural map exploration strategies. Finally, another possibility was implementing a double tap rather than a single tap because it is less likely to occur by chance (Yatani et al., 2012).

Therefore we decided to implement a double tap interaction. Kane, Wobbrock, and Ladner (2011) identified single and double taps as gestures that are easily usable by blind people. Yatani, Banovic, and Truong (2012) confirmed the validity of the double tap interaction in their study. Multiple tap interaction was also used in the Talking TMAP project (Miele et al., 2006) and by Senette et al. (2013). Figure III.15 shows the Double Tap state machine. Each map object possessed its own double tap state machine for handling its internal state. We made the choice to end the double tap after the second tap while still touching the surface. This allowed the users to rest their fingers on the interactive map element that they had chosen. Our pretests showed that this implementation was more natural for visually impaired users than to remove their finger from the point that they selected. Resting the finger on the element is helpful for remembering the position of elements. We implemented a double tap technique with a 700 ms delay between two taps. The standard speed for mouse double clicks in Windows Operating System, which is 500ms, proved to be too short for the visually impaired users.

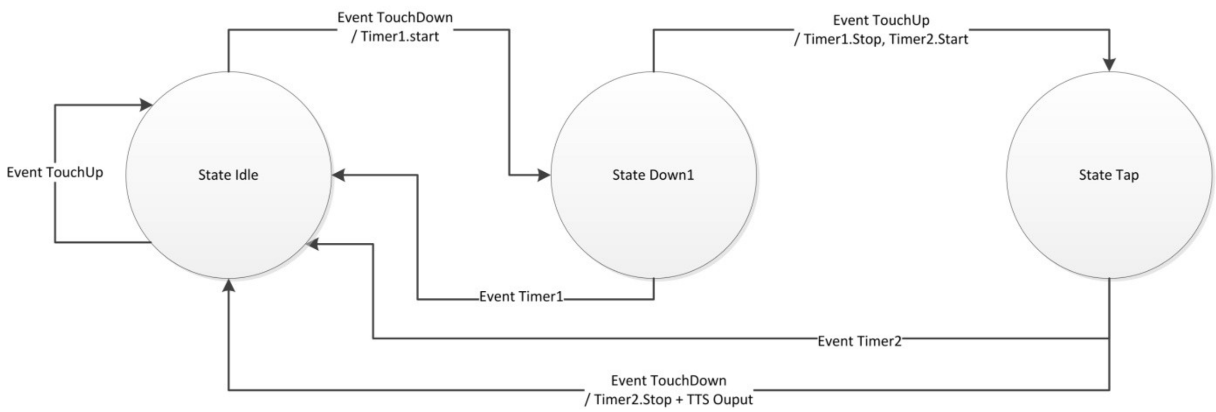


Figure III.15: Double-tap state machine as implemented in the prototype.

Our pretests proved that this double tap technique was efficient. However, some participants needed time to get familiarized with the unknown interacting technique. Unintended double tap interaction occurred, mainly because of the palms of the hand placed on the map during exploration (Buxton, 2007). We therefore asked users to wear mittens during map exploration, which minimized the occurrence of unintended touch inputs (Figure III.17).

III.2.5.3.b Speech Output

Speech is a powerful means of communicating information non-visually (see II.4.4.1.a). Most studies on intelligibility of TTS systems have been done for English language. In our case we were interested in French-speaking TTS. Côté-Giroux et al. (2011) studied intelligibility of nine different French-speaking TTS systems in comparison with a human voice. They compared 61 sighted participants across three age groups and two conditions (with or without context). The nine TTS systems included male and female voices and had a different price range. Their study revealed a significant effect of the voice on intelligibility. The two female voices Louise (Acapela) and Virginie (Nuance RealSpeak) revealed to be almost as intelligible as a human voice. Interestingly, even the human voice did not have a perfect intelligibility. Furthermore, a significant effect of condition emerged. Words in context were more intelligible than outside the context. The difference was bigger for voices with poor intelligibility. In what concerns appreciation, there was again a significant effect of voice. Human voice was more appreciated than any of the synthetic voices except for Virginie. Most appreciated voices were described as suave, fluid, warm and expressive. Finally, the study revealed a positive correlation between intelligibility and appreciation of a voice. The overall best results concerning both intelligibility and appreciation were received for voices Acapela (Bruno and Louise), Nuance (Virginie, Sophie) and Loquendo (Olivier).

During the development we tested different types of speech output. In the prototypes that were based on modular software architecture, we used PPilot, an ivy-module created in our research group using Realspeak SAPI (Microsoft Speech API). In a first prototype, we used the Realspeak SAPI 5.0 with French voice "Virginie" (Nuance)—sampled with 16 KhZ—for its good intelligibility and user appreciation. In a second step, we used the RealSpeak SAPI 4.0 TTS with the French female voice "Sophie" for the same reasons. A comprehensible pronunciation was assured by controlling the TTS settings. Concretely, it was important that users perceived the TTS as comfortable regarding volume, pace and voice. We set a standard pace, although blind users are mostly used to screen readers at a high pace (Asakawa et al., 2003). This choice was made to ensure that users would understand single unknown words, even out of context and with non-familiar voices. Speakers were connected to the computer. The volume of the speech output was kept constant at an audible level during all the experiments.

Prototypes that were based on a single application instead of a modular software architecture could not make use of the PPilot module for TTS. We replaced it with a java-based application, the S.I. VOX / Vocalyze software[41]. This software was developed by the University of Nice Sophia Antipolis for a project with visually impaired people and made available under free license. It was based on the MBROLA project[42] (Dutoit, Pagel, Pierret, & Bataille, 1996). The MBROLA project provided a set of speech synthesizers for different languages under a free license for non-commercial applications, especially for academic research. MBROLA itself is not a Text-To-Speech (TTS) synthesizer, as it does not accept raw text as input. Instead, the MBROLA speech synthesizer is based on the concatenation of diphones. The input is a list of phonemes together with prosodic information—duration of phonemes and a piecewise linear description of pitch. It produces speech samples on linear 16 bits at the sampling frequency of the diphone database used. The S.I. VOX / Vocalyze software then provides a wrapper around MBROLA so it can be used as a TTS.

III.2.5.4 Iterative Development of Prototypes

The previously described design possibilities have been put together in several prototypes. We developed these different prototypes to explore the possible design space concerning combinations of interaction techniques and technologies. All applications were developed on a HP EliteBook 8530p connected to the multi-touch device.

III.2.5.4.a First Interactive Map Prototype

The objective of this prototype was to develop a first functional interactive map before acquiring the necessary hardware for the further development. For this prototype we used the display of the Stantum SMK-15.4 Multi-Touch Development Kit[43], the Ivy-based modular architecture, the second map drawing (III.2.5.1), simple tap touch interaction, and Realspeak SAPI 5.0 with French voice "Virginie". Figure III.16 shows a user exploring the prototype.

Several possibilities existed for accessing touch information with the Stantum device (see Brock, 2010 for details). We drew inspiration from the "Stantum Tuio Bridge" (Hoste, 2010) that converted the touch events from the Stantum touch device into the TUIO

[41] http://users.polytech.unice.fr/~helen/SERVER_SI_VOX/pages/index.php?page=Accueil [last accessed June 10th 2013]

[42] http://tcts.fpms.ac.be/synthesis/ [last accessed June 10th 2013]

[43] http://www.stantum.com/en/ [last accessed June 10th 2013]. Stéphane Chatty (ENAC LII Lab) generously lent us the Stantum SMK-15.4 Multi-Touch Development Kit during the development of the first prototype.

protocol (Kaltenbrunner, Bovermann, Bencina, & Costanza, 2005). TUIO is a middleware that works in connection with various tabletop devices. It is based on communication between the object recognition layer and the interaction layer for any hardware. Today, TUIO is a standardized solution that is widely adopted for implementing multi-touch applications.

Figure III.16: Visually impaired user exploring the interactive map prototype

The original "Stantum Tuio Bridge" had been implemented for a Linux system. We implemented the driver in C++ and adapted it for Windows operating system. The driver received touch input directly from hardware and sent it to the ivy bus (see subsection III.2.5.2). We faced some challenges concerning the resolution of the screen as the original TUIO Bridge had been used with a 480*800 pixel device. To facilitate conversion between different screen resolutions, we used the display with a 1360*768 resolution instead of the default resolution. This conversion resulted in a small imprecision of the calculated position that we compensated for in the map drawing.

Our objective was to distinguish exploratory finger movements (i.e., touching the screen for following the raised-lines on the map) from touch interaction (i.e., pressing the screen). The hardware provided the possibility to differentiate "touch down" events (finger pressing), "move" events (finger moving while touching the screen) and "up" events (finger contact leaves the screen). For each cursor the normal event flow should be "down", optionally "move" and then "up". In the application we treated only "touch down" events as these are the events at the origin of each touch interaction.

Pretests of the prototype with three blind users as reported in section III.2.5.2.b made us recognize the need to adapt the interaction technique from simple tap interaction to double tap interaction.

III.2.5.4.b Second Prototype: the Experimental Prototype

In the next step, the objective was to develop a high-fidelity prototype that could be used for a user study. For this prototype we used the display 3M™ Multi-touch Display M2256PW, the Ivy-based modular software architecture (III.2.5.2), the third map drawing (IV.2.1.1), double tap touch interaction and RealSpeak SAPI 4.0 TTS with the French female voice "Sophie". Figure III.17 shows a photograph of a user exploring the interactive map prototype.

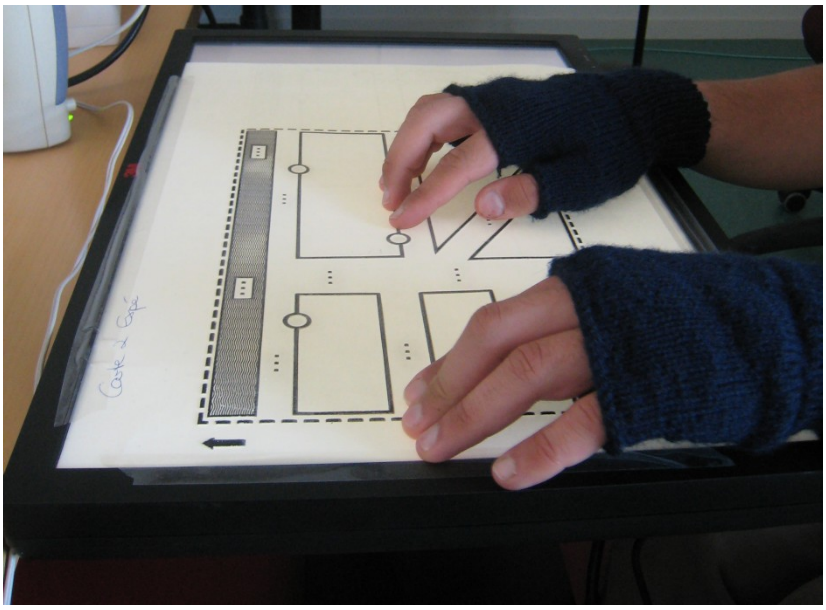


Figure III.17: Photograph of a user exploring the interactive map. The raised-line map overlay is attached on top of the touch screen. The user is wearing mittens to prevent unintended touch input from the palms.

As we changed the touch display we needed to adapt the Touch Detection Module. This module handling the touch input was coded in C. We used the touch screen low level driver, as we wanted to directly access precise touch information. For each touch event, we obtained an ID, coordinates and a timestamp. This information was then sent to the second module (Viewer Module). The Interactive Map Module was coded in Java as before and received messages from both modules. It implemented the state machine for the double tap interaction.

We checked with a blind subject that the double tap interaction was efficient, that speech output was intelligible, and that the voice, volume and pace were adapted and comfortable. The usability of the interactive map and the raised-line map with braille were then compared in a usability study with 24 blind users (see chapter IV).

This prototype was voluntarily limited to very basic functionality as we wanted to compare it with a tactile map with braille legend.

III.2.6 Evaluating Usability and Accessibility

In a user-centered design process, evaluation can be done by usability experts based on heuristics, guidelines or standards (ISO, 2010) or by automatic checking of guidelines. However, to be sure of a product's usability or accessibility, it is necessary to do tests with real users (Petrie & Bevan, 2009). When designing for impaired users, it is especially important to include the target audience in evaluations (Henry, 2007). In our first experimental study (see chapter IV), we aimed to compare the three aspects of usability (effectiveness, efficiency and satisfaction (ISO, 2010)) of two different map types (paper and interactive). For this purpose, we needed to prepare appropriate evaluation methods. We evaluated effectiveness as spatial cognition with the help of a battery of spatial orientation tests. User satisfaction has been evaluated with a dedicated questionnaire. In the following subsections we explain how we chose these tests and questionnaires.

III.2.6.1 Spatial Orientation Tests

Our project required tests for assessing spatial cognition of users after exploring different map types. In subsection II.2.2.5 we have described different tests for evaluating spatial knowledge of visually impaired people. We mainly based our test battery on the propositions of Kitchin and Jacobson (1997) and Bosco et al. (2004). We chose tests that could be answered orally, to avoid problems with sketch mapping. Furthermore, we followed the suggestion to propose multiple tests for one type of spatial knowledge, so that users would get the chance to compensate for shortcomings with one type of question and to avoid methodological biases (Kitchin, 1996). For instance, one series of questions in our battery relied on the clock face method, whereas another series relied on cardinal directions. This example is substantial as some blind people are used to the clock face method, whereas others prefer using cardinal directions to orient themselves.

We defined a test battery made of questions relative to landmark, route and survey knowledge. Landmark knowledge corresponds to the detection of points of interest, thus their presence, name and eventually features—such as shape or smell—without taking into account spatial relation between different points. As there was no prior work on accessible tests for evaluating landmark knowledge, we developed our own battery. In our study, we evaluated landmark knowledge as the storage of names in memory.

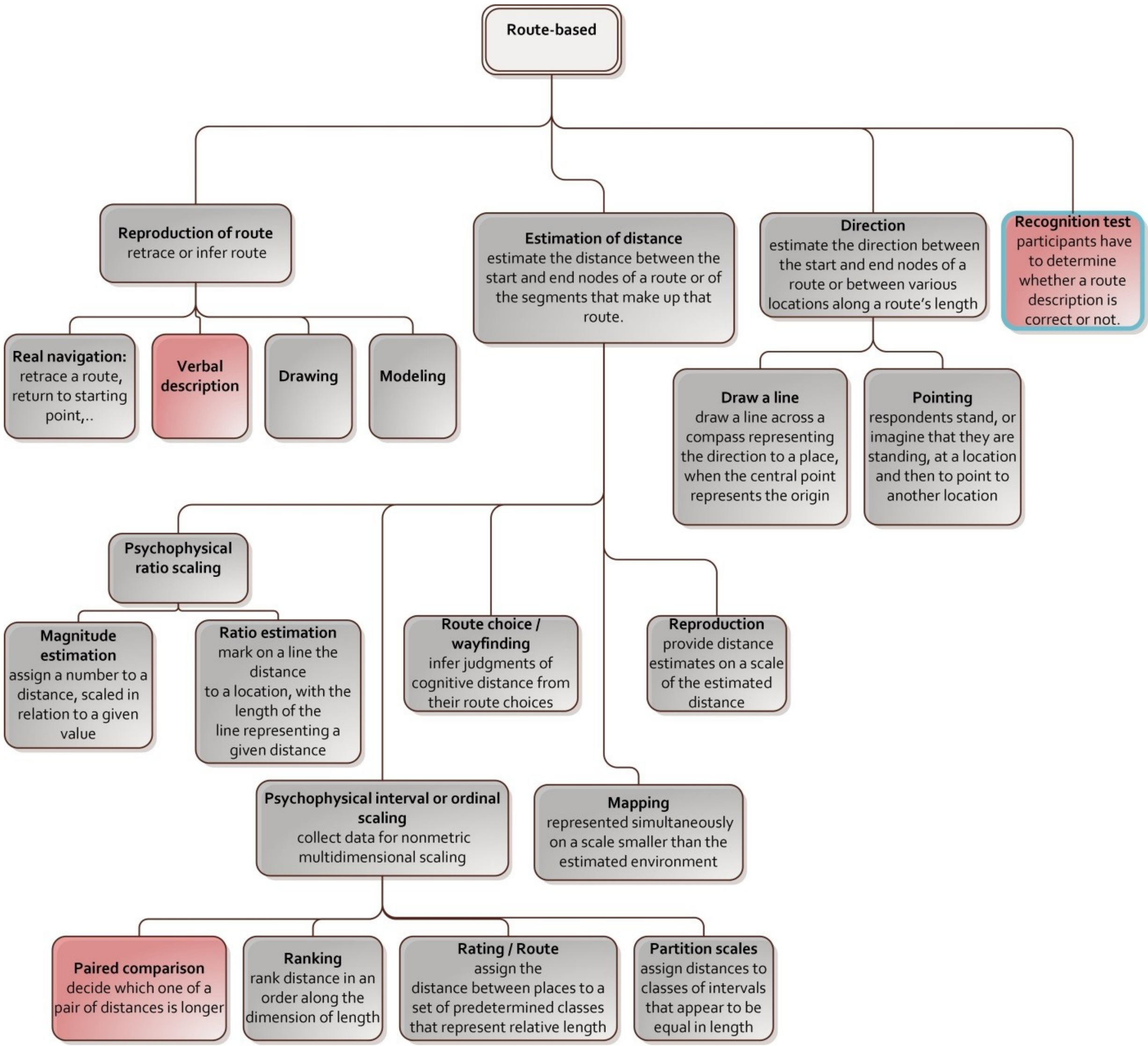


Figure III.18: Methods for evaluating route-based knowledge with visually impaired people integrated into the classification by Kitchin and Jacobson (1997). Red filling: methods included in our test battery. Blue outline: method that we added to the classification.

Route-based tests assess participants' knowledge on how to travel between points of interest. Kitchin and Jacobson (1997) proposed several methods for evaluating route knowledge (see Figure III.18). In our battery we chose three route tests. 1) Route distance estimation ("R-DE"): two couples of POI were proposed (e.g. museum - spa vs. railway station - obelisk) and participants had to select the two points separated by the longest route when following the roads (also called functional distance in Ungar, 2000). This method was based on the "paired comparison" method that is part of the psychophysical ordinal scaling techniques, a sub-category of distance estimation (Kitchin & Jacobson, 1997) and route distance judgment (Bosco et al., 2004). According to Kitchin and

Jacobson (1997), these methods might have more utility for measuring visually impaired people's distance knowledge than magnitude or ratio estimation techniques because they require only categorization rather than more precise scaling estimates. 2) Route recognition ("R-R"): a route between two points was described and participants had to decide whether the description was correct or not. This test has originally proposed by Kitchin and Jacobson (1997) as part of the tests on survey knowledge but not on route knowledge. Yet, it was included in Bosco's battery on spatial orientation tests (Bosco et al., 2004). 3) Wayfinding ("R-W"): A starting point and a destination were provided and the participants had to describe the shortest route between these two points. Whereas Bosco et al. (2004) indicated the route description and participants had to determine the arrival point, in our test battery participants had to determine the route description. This test set was the verbal description variant of the reproduction of route method (Kitchin & Jacobson, 1997).

Configurational or survey tests evaluate knowledge of the spatial relation between landmarks. Figure III.19 shows methods for evaluating survey knowledge based on Kitchin and Jacobson (1997). For our test battery we chose three configurational tests. The first test set was direction estimation ("S-Dir"): a point of interest and a goal point were given and participants had to indicate the direction to the goal using a clock system (e.g. three o'clock for direction east). Kitchin and Jacobson (1997) had proposed direction estimation only for evaluating route knowledge and not for survey knowledge. However we believe that this method is appropriate for evaluating configurational knowledge concerning direction between landmarks. The second set of questions was location estimation ("S-Loc"): the map was divided into four equivalent parts (northeast, northwest, southeast, southwest), and participants had to decide for a map element in which part it was located. We introduced this method as a variant of the "spatial cued response" (see Figure III.19) which is a partial reconstruction test (Kitchin & Jacobson, 1997). The third set of questions was survey distance estimation ("S-Dist"): two pairs of POI were proposed (e.g. museum - railway station vs. spa - obelisk), and participants had to decide which distance was the longest one in a straight line (Euclidian distance). This method has been proposed both by Kitchin and Jacobson (1997) and Bosco et al. (2004).

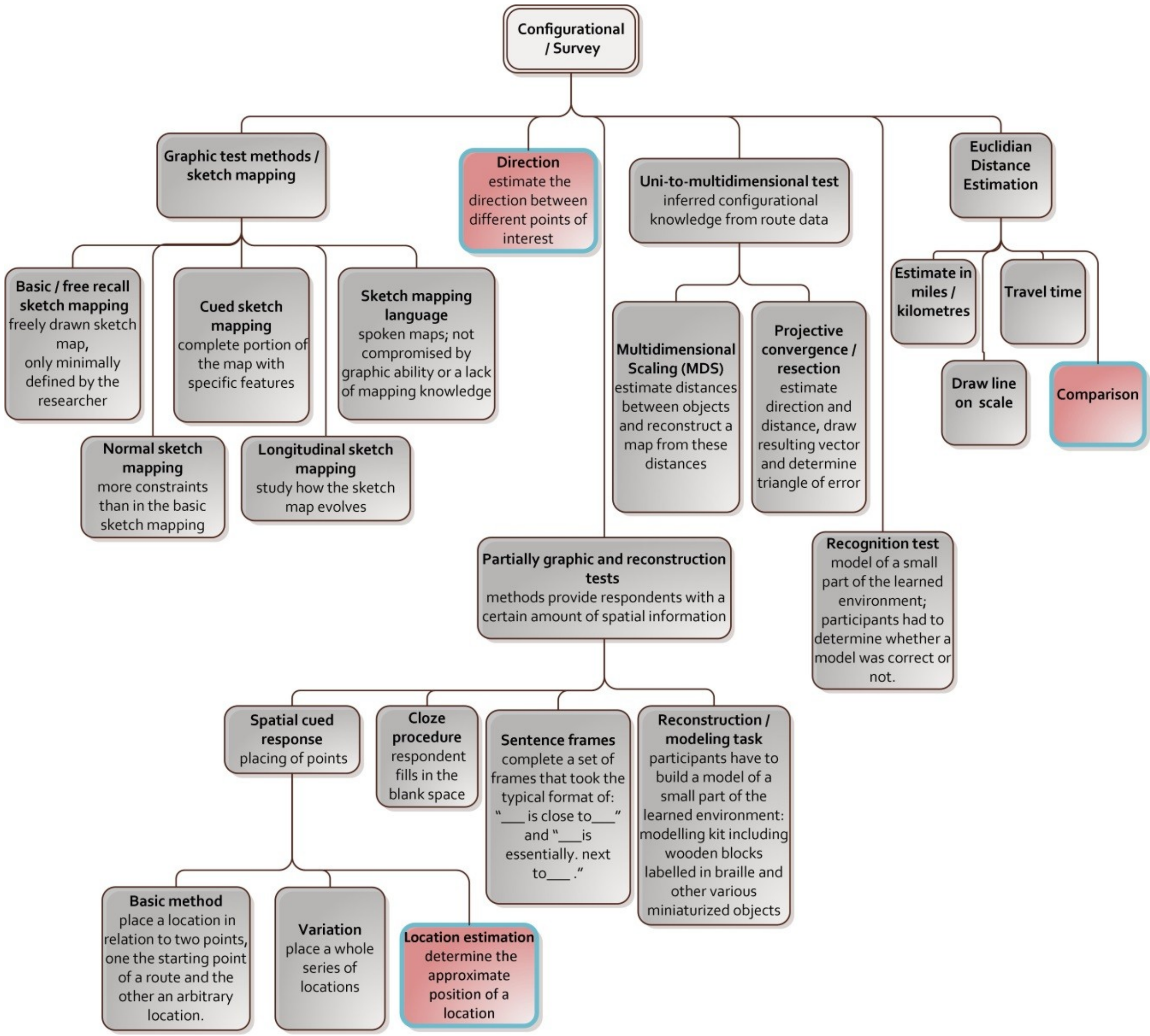


Figure III.19: Methods for evaluating survey knowledge with visually impaired people integrated into the classification by Kitchin and Jacobson (1997). Red filling: methods included in our test battery. Blue outline: method that we added to the classification.

III.2.6.2 Questionnaire for Evaluating User Satisfaction

Satisfaction—positive attitudes towards the use of the product—was evaluated with quantitative and qualitative questionnaires. In order to choose an adapted questionnaire, we analyzed different standardized questionnaires.

The SUS (System Usability Scale, Brooke, 1996) is a questionnaire designed for accessing user satisfaction. It is composed of 10 questions on a 5 point Likert scale. Positive and negative responses are alternated for counterbalancing. The SUS is free to use.

Lewis (2009) presented four different questionnaires used at IBM: ASQ, PSQ, PSSUQ and CSUQ. The ASQ (after scenario questionnaire) is a 7 point Likert scale, composed of three questions on ease of task completion, time for completing a task and usefulness of help. It is mainly used for scenario-based evaluation. The PSQ (printer scenario questionnaire) is an older version of the ASQ on a 5 point Likert scale. The PSSUQ (post study system usability questionnaire) is a 7-point Likert scale composed of 19 questions. Four different scales can be calculated: overall satisfaction, system usefulness, information quality and interface quality. The CSUQ (computer system usability questionnaire) is a version of the PSSUQ used for field testing. Questions are similar than for the PSSUQ with the difference that they do not relate to specific tasks but to the work in general. The IBM questionnaires are free for use.

The SUMI (Software Usability Measurement Inventory, Kirakowski & Corbett, 1993) is composed of 50 questions with three possible reponses ("agree", "don't know", "disagree"). In comparison to the preceding questionnaires, the SUMI is distributed commercially (although free licenses can be obtained for teaching). It exists in different languages, with the different versions validated by native speakers.

Other questionnaires evaluate related issues. For instance, the NASA-TLX measures workload (Hart & Staveland, 1988). A higher workload might result in a lower satisfaction. However this is purely speculative and the questionnaire does not evaluate satisfaction as such. The AttrakDiff questionnaire (Hassenzahl, Burmester, & Koller, 2003) goes beyond user satisfaction as it is intended for evaluating heuristic quality (stimulation and identity) and attractiveness of a system.

As in our study we wanted to evaluate usability only, we focused on ASQ, PSSUQ, SUMI and SUS which are all mentioned as questionnaires for usability testing in the common industry format for usability testing (*ANSI INCITS 354-2001 Common Industry Format Usability Test Reports*, 2001). They are also often used in Human-Computer-Interaction research on usability. With only three questions, the ASQ appeared too short. ASQ and PSSUQ contained questions that did not apply to our system (for instance about help functionality). The SUMI on the other hand with 50 questions seemed very long. Besides, Wechsung and Naumann (2008) had observed that results from the SUMI questionnaire did not correlate with results from other user satisfaction questionnaires. For these reasons the SUS seemed the best adapted.

III.2.6.3 Usability Testing

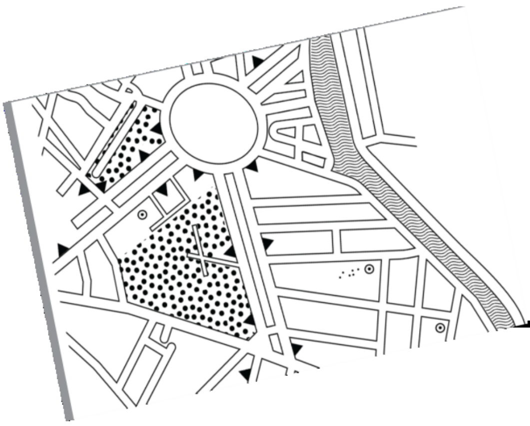
As described above, several evaluations with users have been done during the iterative design process. This allowed us to improve prototypes steadily through the different iterations of the cycle. Yet, we also aimed to do a methodological user study. In the next chapter (IV), we present this study in which we compared usability of an interactive map with usability of a raised-line map with braille. The battery of accessible spatial tests and the SUS questionnaire as presented above were used in this study.

III.3 Conclusion

In this chapter we presented our contribution to the development of interactive maps for visually impaired people.

We responded to Research Question 1 (What is the most suitable design choice for interactive maps for visually impaired people). As it is impossible to define a universal best solution, we defined a precise context of use. Concretely our aim was to develop a prototype that allowed a visually impaired person to explore an unknown geographic area. We did not aim at providing a prototype for mobile interaction, but for exploring a map at home, at school or in another "immobile" context. Based on the analysis of the design space of interactive maps for visually impaired people (see II.4), we opted for an interactive map design composed by a multi-touch screen, a raised-line map overlay and speech output. This design choice was also based on visual impaired users' contribution to the design process. We presented different versions of each map component that have been developed through an iterative process. We also presented the experimental prototype that was used in a subsequent user study (see chapter IV). Based on the experience of designing interactive maps we can propose guidelines for the different map components (see VII.6.3)

Furthermore, we replied to Research Question 2 (How to involve visually impaired people in a participatory design process?) as we worked in a close collaboration with the Institute of the Young Blind (Institut des Jeunes Aveugles) in Toulouse for adopting an accessible participatory design process. To this end, it was necessary to adapt these methods to working with visually impaired people as many participatory design methods are based on the use of the visual modality. Previous studies have investigated this subject, but there is still a lack of accessible methods for working with visually impaired people. From our experience we can give recommendations as presented in VII.7.



Chapter IV

Usability of Interactive Maps and their Impact on Spatial Cognition

IV Usability of Interactive Maps and their Impact on Spatial Cognition

This chapter[44] responds to Research Questions 3 (How usable is an interactive map in comparison with a tactile paper map?) and 4 (How does an interactive map contribute to spatial cognition?). We present a detailed comparison of usability of two different geographic map types for visually impaired people: a classical raised-line map vs. an accessible interactive map composed by a multi-touch screen, a tactile map overlay and audio output. Both map types were tested by 24 blind participants. We measured usability of the map as efficiency (learning time), effectiveness (spatial knowledge) and satisfaction. Our results show that replacing the braille legend with a simple touch and audio interaction significantly improved efficiency of the map and satisfaction of the users. Spatial cognition is part of usability, but it is even richer when analyzed from a perspective of cognitive science. Therefore we considered it interesting to more closely analyze spatial cognition. Improvement in spatial learning depended on users' expertise and characteristics as well as the type of spatial knowledge (landmark, route, survey).

In a second study, we measured the effect of time on spatial information acquired from the two different map types. We did not observe any global influence of map type on long-term spatial recall, i.e. two weeks after exploration. Significant differences, however, were observed according to the type of spatial knowledge (landmark, route and survey). This study proves that it is possible for visually impaired people to acquire spatial knowledge in the long-term by using either a raised-line or an interactive map.

To sum up, these results show that interactivity is promising for improving usability and accessibility of geographic maps for visually impaired people. The design of non-visual interactions that promote essential spatial tasks (e.g. retrieving distances and directions) may greatly enhance accessibility.

IV.1 Evaluating Usability with Visually Impaired People

Usability is an important measure for evaluating a system in Human-Computer Interaction. It is defined as "the extent to which a system [...] can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" (ISO, 2010).

[44] Note : a paper presenting this chapter is currently under submission. Part of the results have been published in (Brock, Truillet, et al., 2012).

Few studies compared usability of different systems for visually impaired people. As an example, Giudice et al. (2012) evaluated a vibro-audio tablet interface against a tactile image for learning non-visual graphical information, both with blind and blindfolded participants. The vibro-audio tablet interface synchronously triggered vibration patterns and auditory information when the users touched an on-screen element. The tactile graphic was embossed and did not offer any additional feedback than the embossed relief. In this study, learning time with the interactive prototype was up to four times longer than with the paper diagram. Also users had more problems to follow lines and curves when indicated by vibrations than when printed in relief. This finding raises the question if interactive devices are less usable than dedicated tools.

Wang et al. (2012) compared an interactive map (with raised-line map and audio output) against a tactile map without any textual information. Users preferred the interactive map. Furthermore, they observed that the interactive map was quicker in 64% of all cases for identifying start and end points but not for route exploration. This comparison is limited as in the interactive condition users spent most time on listening to the audio output, whereas the tactile map did not contain any braille information.

Although it appears crucial, no prior study compared the usability (i.e., effectiveness, efficiency, and satisfaction) of an interactive map with the usability of a classical raised-line map with braille. Therefore, designers and researchers missed the confirmation that interactive maps do not raise accessibility or cognitive issues, and that they are equivalent or even better solutions than traditional embossed maps. Three possible outcomes exist for such study: the interactive map could be more, equal or less usable for visually impaired people than a classical raised-line map. If interactive maps were less efficient, less effective or less satisfying than raised-line maps the first research effort should determine why. Then, the design of interactive maps should focus on usability, ensuring that appropriate methods are used for evaluation. On the contrary, if interactive maps are equivalent or even better solutions than regular embossed maps, designers would know that interactive maps do not raise accessibility or cognitive issues. They should then focus on the design of non-visual interaction applied to map exploration and spatial learning.

Consequently, in order to fill this gap, this chapter presents a study on the usability of two different geographic map types for visually impaired people: a classical raised-line map compared to an accessible interactive map as described in subsection III.2.5.4.b.

IV.2 Material and Methods

The goal of this study was to compare usability of two different map types for visually impaired people: a raised-line paper map (PM) and an interactive map (IM). Our general hypothesis was that an interactive map (IM) was more usable than a tactile paper map (PM) for providing blind people with spatial knowledge about a novel environment. As previously reported, usability can be measured as the effectiveness, efficiency and satisfaction with which specified users achieve specified goals in a specified context of use (ISO, 2010). In this study, the users were visually impaired people. The context of use was map reading and the specified goal acquiring spatial knowledge about a novel environment. We made the following specific predictions concerning the three factors of usability:

1) Efficiency is defined as the resources expended in relation to the accuracy and completeness with which users achieve goals (ISO, 2010). A common measure of efficiency is time on task, but efficiency may also relate to other resources (*ANSI INCITS 354-2001 Common Industry Format Usability Test Reports*, 2001). In our study, we predicted a shorter exploration time devoted to map learning for IM than for PM. This reasoning was based on the fact that PM was accompanied by a legend. The alternation between map exploration and legend reading introduces a disruption which does not exist with the interactive map (Hinton, 1993).

2) Effectiveness is defined as the accuracy and completeness with which users achieve specified goals (ISO, 2010). It only considers the extent to which task goals were achieved and not how this was done. Effectiveness is commonly measured as completion rate, error rate, frequency of assist to the participant from the tester or frequency of accessing help or documentation (*ANSI INCITS 354-2001 Common Industry Format Usability Test Reports*, 2001). In our study effectiveness was measured as the completion rate of acquisition of spatial knowledge. We predicted that participants would acquire more profound spatial knowledge with IM than with PM. This is based on the assumption that adding an auditory component to maps (hence providing multimodal input) is more beneficial than using tactile information alone (Golledge et al., 2005).

3) Satisfaction is defined as the freedom of discomfort and positive attitudes towards the use of the product (ISO, 2010). It is common to assess satisfaction with a Likert-scale questionnaire (*ANSI INCITS 354-2001 Common Industry Format Usability Test Reports*, 2001). We predicted that IM would yield higher satisfaction scores than PM. Previous studies observed a high satisfaction rate when visually impaired people used interactive devices (see for instance Kane, Morris, et al., 2011). We made the assumption

that users would perceive the interactive map as more accessible and ludic. Moreover we hypothesized that users who encounter difficulties with braille reading would prefer audio output.

IV.2.1 Material

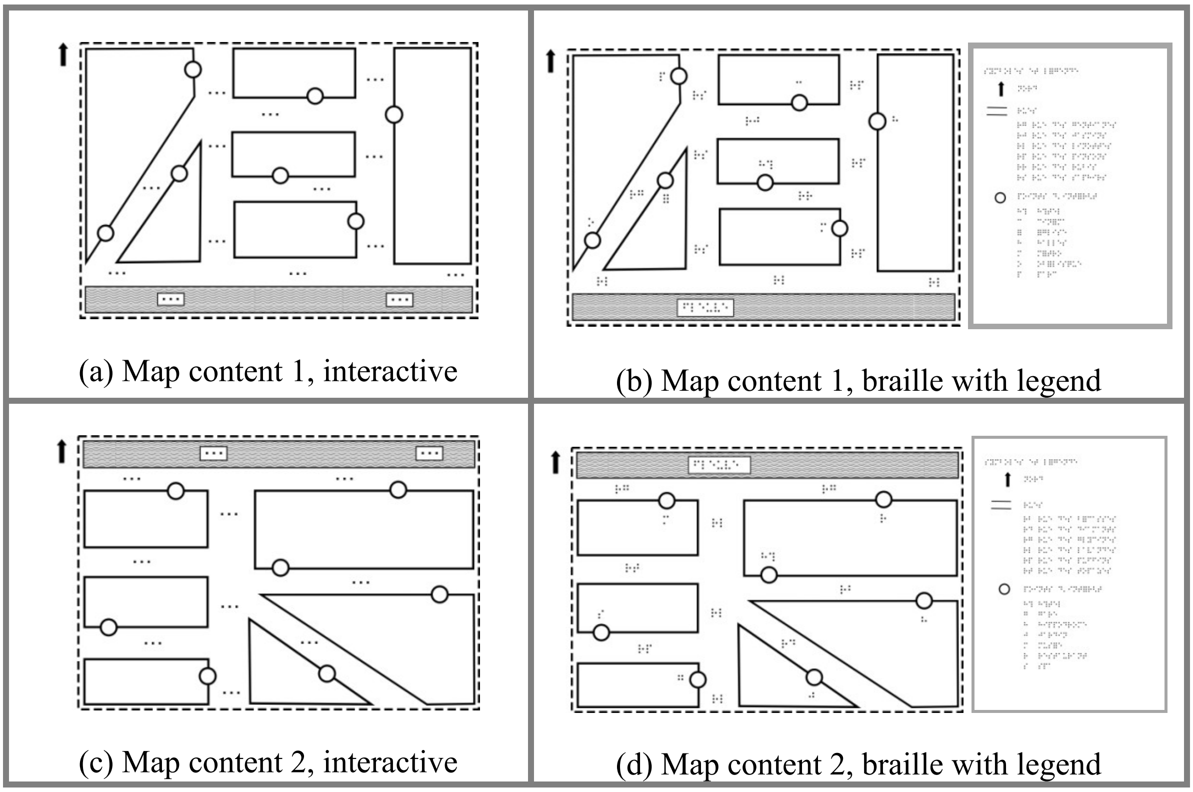
We tested the same raised-line maps under two different conditions ("map type"): the paper map (PM) condition corresponded to a regular raised-line map with braille legend; the interactive map (IM) condition corresponded to a touch screen with a raised-line map overlay (without any braille text) and audio feedback. The interactive map was functionally comparable to a regular tactile paper map. Users could explore the raised-line map on top of the screen with both hands, i.e. ten fingers, exactly the same way that they would explore a paper map. Exploratory movements did not produce any speech output. The braille legend was replaced by audio output that was triggered through a double tap on the markers. No further input or output interaction was provided to ensure functional equivalence with the paper map. The design of the interactive map is presented in subsection III.2.5.4.b.

IV.2.1.1 Raised-line Map Design

We previously explained the design and production of raised-line maps for visually impaired people (see II.3.3 and III.2.5.1). The map that was produced for the experimental prototype was a simplified version of the tactile maps presented in subsection III.2.5.1. As in previous prototypes, we used A3 format swell paper of the brand ZY®-TEX2. Maps were printed in landscape format with a Toshiba e-STUDIO 355 copier. For the braille legend we used A4 paper printed in portrait format with a Dell 3330dn Laser Printer XL. In both cases we used the same Piaf fuser for creating the relief. Embossment of microcapsule paper maps is altered after several uses. Therefore, we printed out a new exemplar after the map had been used five times. We validated that this was sufficient to maintain quality and readability of the maps over the whole experiment.

Same as the previously mentioned maps (III.2.5.1), the maps were designed as SVG maps with Inkscape. A dashed line (line width 1.4 mm; miter join; miter limit 4.1; butt cap; no start, mid or end markers) presented the outer limits of the map. Streets and buildings were separated by a solid line (line width 1.4 mm; miter join; miter limit 4.0; butt cap; no start, mid or end markers). A texture represented a river (texture "wavy"). Points of interest (POI) were represented by circles (width and height 12.4 mm, line width 1.4 mm). An arrow on the left upper side of the map indicated the north direction.

To avoid that newly learnt spatial knowledge would interfere with previous knowledge (Thinus-Blanc & Gaunet, 1997), we chose to represent a unknown environment. We designed a first map (see Figure IV.1) representing a fictional city center with six streets, six buildings, six points of interest (for example museum, restaurant, and public transportation) plus a hotel in the center of the map as well as one geographic element (a river). A second map was then created with the same map elements that were rotated and translated, so that both map contents were equivalent. The additional central point of interest in the middle of the map (hotel) was common for both maps. Pretests with a visually impaired user ensured that the maps were readable. We also assured that they were not too easy or too difficult to memorize in order to avoid a ceiling or floor effect concerning the observed variables.



(a) Map content 1, interactive

(b) Map content 1, braille with legend

(c) Map content 2, interactive

(d) Map content 2, braille with legend

Figure IV.1: Four different variants of the map existed in total. Two different map contents are depicted in (a, b) and (c, d). They are based on the same geographic elements, which were rotated and translated. Both map contents exist with braille (b, d) and in interactive format (a, c). Circles are points of interest (either interactive or accompanied by a braille abbreviation). The marks composed by three dots are interactive elements to access street names.

IV.2.1.1.a Lexical Content

We assured the lexical equivalence between maps by means of the "Lexique" database (New, Pallier, Ferrand, & Matos, 2001). The Lexique database analyzed French subtitles of current American movies as a corpus for their database. We considered two criteria for inclusion of text: the frequency of oral usage (number of occurrences per million) as well as the number of syllables. The first point was considered important because of the word frequency effect: in general more frequent words are easier to memorize than less frequent words (Grainger, 1990). The second was considered important because shorter words are better recalled than longer words (Baddeley, Thomson, & Buchanan, 1975). Another constraint was that words on each map had to begin with different letters so that each braille abbreviation was unique. Detailed tables with the lexical map content can be found in the appendix VII.6.2. To sum up, all street names were composed of two syllables, and were low frequency words, i.e. words with less than 20 occurrences per million. In addition we used categories for the names: on each map two streets were named after birds, two after precious stones and two after flowers. On each map there were 6 points of interest (POI) with counterbalanced frequencies and number of syllables. In addition to these six POIs, we added a reference point on both maps which was the hotel. The word "hotel" had the highest usage frequency among all POIs that we selected.

IV.2.1.1.b Specificities Raised-line Map with Braille Legend (PM)

In regular raised-line maps, braille legends provide information on the different map elements. Normally numbers or abbreviations are positioned on the map close to the elements that they describe. These markers are then found in the legend with additional textual information. We used abbreviations rather than numbers as they facilitate the cognitive association with the full name of the element. For instance it seems easier to remember the letter M for Museum than number 5.

In our map all street name legends began with the word "rue" (French translation for "street") followed by the name of the street (note: in French an article between both words is required). The corresponding abbreviation was the letter "r" followed by the initial of the street name. For example "rue des saphirs" (Sapphire street) was abbreviated "rs". POIs were abbreviated with the initial of their name (for example "museum" was abbreviated with the letter "m"). The braille legend was printed on a separate A4 sheet of paper which was placed next to the map. Text was written in uncontracted braille with the font "Braillenew" (font size 32 and line spacing 125%).

IV.2.1.1.c Specificities for the Interactive Map (IM)

The drawing for the interactive map included particular zones and elements that were interactive (see Figure IV.1). Streets names were located with three dots (font DejaVuSans, normal, font size 47.5, line spacing 125%). These marks were repeated between crossings of the same street to avoid ambiguity. The circles representing POIs were made interactive without any additional mark.

IV.2.2 Participants

As stated in the previous chapter (III.2.2), we recruited visually impaired participants from different associations, through a local radio broadcast for visually impaired people as well as by word-of-mouth. All participants gave informed consent to participate in the whole experiment over the duration of three weeks. They received a gift certificate after completion of the study. Costs for transportation were also reimbursed. None of the participants had seen or had knowledge of the experimental setup, or been informed about the experimental purposes before the experiment.

We prepared Google forms as questionnaires on users' characteristics. Users were supposed to fill out the questionnaires themselves before the session. However, pretests showed that these questionnaires were challenging regarding accessibility. We therefore decided to do interviews instead of questionnaires (Brock, Vinot, et al., 2010). The questionnaire can be found in appendix VII.8.1.

Subject	Gender	Chronological age (yrs)	Age at onset of blindness (yrs)*	Etiology of blindness	Occupation
1	F	31	2	iritis	lawyer, certified public accountant
2	F	58	0-15	congenital	administrative occupation
3	M	25	0	optical neuritis	student (communication technologies)
4	M	21	14-15	infectious disease	student (languages)
5	F	33	25-27	retinitis pigmentosa	front office employee (in training)
6	M	53	0-19	infectious disease	furniture manufacturer
7	M	31	5	accident	furniture manufacturer
8	F	54	0	optic atrophy	teacher (Braille)
9	F	38	0	retinitis pigmentosa	front office employee (unemployed)
10	F	64	0-10	genetic disease	retired physiotherapist
11	M	48	25	accident	physiotherapist
12	M	59	0	retrolental fibroplasia	teacher (computer science)
13	F	42	0-15	genetic disease	beautician
14	M	62	5	congenital	retired engineer
15	F	51	6	retinoblastoma	teacher (mathematics)
16	M	51	0	retrolental fibroplasia	telephone operator
17	F	58	0	genetic disease	retired teacher (Braille)
18	M	25	0-1	genetic disease	assistant secretary (in training)
19	M	33	0-14	glaucoma	translator (in search for a job)
20	F	36	0-12	glaucoma	front office employee (in training)
21	M	31	0-19	glaucoma	songwriter, pianist
22	F	41	0	retrolental fibroplasia	teacher (music)
23	F	27	13	retinal detachment	teacher (Braille)
24	M	39	6	infectious disease	software developper

Figure IV.2: Description of the visually impaired participants in our study. Means and SDs have been omitted from this table. *When blindness was progressive, two values are reported (the second value indicates the age at which blindness actually impaired the subjects' life).

Figure IV.2 shows the list of participants with some of their personal characteristics. Further characteristics—education, travel aids and use of new technology—are reported in the appendix VII.8.1. Henry (2007) recommended to recruit users with varying characteristics within the actual target audience. 24 legally blind participants (12 women, 12 men) participated in the study. Chronological age varied from 21 to 64 years (mean chronological age = 42 years, *SD* = 13.15). The age at onset of blindness varied from 0 to 27 (*M* = 8.71, *SD* = 8.51). We used the proportion of life-time without visual experience (Lebaz et al., 2010) as measure in our study. This value varied from 0.24 (meaning that the participant spent 24% of his life without visual experience) to 1 (meaning that the participant was born blind). The mean value was 0.87 (*SD*: 0.23).

The blindness of the subjects had different etiologies, including different illnesses —genetic diseases, infectious diseases, or more specifically iritis, optical neuritis, retinitis pigmentosa, optic atrophy, retrolental fibroplasia, retinal detachment, retinoblastoma, glaucoma—as well as accidents (see VII.2 for definitions of the eye diseases). Some participants could perceive light or large objects when being very close but denied being able to use this residual vision in any form of spatial behavior. None of the participants had a known neurological or motor dysfunction in association with the visual impairment. As stated by Thinus-Blanc and Gaunet (1997) the role of these factors is extremely difficult to evaluate and control. Some individuals show affective reactions to their impairment such as depression, autism or stereotyped behavior patterns, whereas other deal with their impairment very well. Congenital blindness might also lead to a delayed development of sensori-motor coordination which might then impact spatial cognition. It is of course very difficult to evaluate these criteria in a study with visually impaired participants.

Sociocultural level, i.e. education level and current position, are used as a classification criteria in some studies with visually impaired users (Thinus-Blanc & Gaunet, 1997). Participants in our study had varied occupations, such as student, administrative occupation, telephone operator, assistant secretary, front office employee, teacher, physiotherapist, engineer, software developer, lawyer, translator, furniture manufacturer, beautician, songwriter and pianist. Most participants were employed, some were retired. Education level varied from vocational education to university (including PhD).

Hand predominance is one of the factors that are applied in some studies with visually impaired users (Thinus-Blanc & Gaunet, 1997). We examined handedness with the Edinburgh Handedness Inventory (Oldfield, 1971). As users' native language was French, we translated it into French. In addition, we slightly adapted it to better match the context of visual impairment (some of the proposed activities are never or rarely executed by visually impaired people) and shortened to 10 questions. The resulting questionnaire can be found as part of the user study questionnaire in appendix VII.8.1. The scores ranged between 10 and 30 (1 to 3 points per question).

As this study focuses on exploration and learning of topological maps, we were also interested in participants' mobility and orientation skills. All participants used white canes for traveling, but some also used guide dogs or electronic travel aids. Participants' orientation skills were examined as a self-assessed value on a five-point Likert scale. We also used the Santa Barbara Sense Of Direction Scale (SBSOD, Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002). This questionnaire has been applied in previous studies (see for instance Ishikawaa et al., 2008; Pielot & Boll, 2010). Again, we translated it into French and adapted the SBSOD to the context of visual impairment. Question 5 ("I tend to think of my environment in terms of cardinal directions") was extended to "I tend to think of my environment in terms of cardinal directions (N, S, E, W) or in terms of a clock-face." This modification has been proposed because the clock method (also called hour system) is a popular method for orientation among the visually impaired population. It consists of situating the user at the center of an analog watch, facing 12 o'clock. For making the user turn right for instance, one would indicate 3 o'clock (Sánchez, Saenz, & Garrido, 2010). Question 10 ("I don't remember routes very well while riding as a passenger in a car.") was changed to "I do not remember routes very well when I am accompanied" as this seemed more adapted to the context. Finally, the scale was adapted from a 7-point scale to a 5-point Likert Scale, to match the scales of the other questionnaires used in this study. Results have been converted back to the 7-point scale to make them comparable to scales used in other studies. The translated and adapted SBSOD questionnaire can be found in appendix VII.8.3.

IV.2.3 Procedure

In the following section, we first describe the pretests for verifying the correct functioning of the material and the procedure before the actual experiment. Then we describe the main experiment that was composed of a short-term and a long-term study. The short-term study aimed at comparing the usability of the two map types (paper map and interactive map). The aim of the long-term study was to compare the memorization of spatial knowledge from each map two weeks after exposure.

IV.2.3.1 Pretests

Pretests, also called pilot testing, are more important when working with impaired users, as more things are new to the researchers and could go wrong during the study

(Henry, 2007). We organized pretests with 2 blind users (1 man, 1 woman). These pretests were done on a fully functional prototype. The test had three objectives: 1) to validate the interaction techniques, 2) to verify the comprehensibility of the tactile maps (i.e., to test that the different marks and textures used for the map were distinguishable and readable), 3) to verify the experimental protocol of the main study and to work out timing issues as proposed by Henry (2007). As a result of this pretest we adapted the speed of the double tap interaction to 700 ms between the two taps, because users had encountered problems with the initial delay of 500 ms. Regarding the experimental protocol we observed that users mixed up some information from the familiarization map with information from the experimental map that they explored immediately afterwards. One reason was that we had presented the experimental map directly after the familiarization map. In order to minimize the confusion between the two maps during the main study, we introduced an interview between these two steps. Another reason was that street names on both maps were similar so that it was difficult for subjects to differentiate the names of the elements on different maps. As a consequence we chose abstract names for the familiarization map: streets and points of interest (POI) were numbered (street 1 to street 4 and POI 1 to POI 4).

IV.2.3.2 Familiarization Phase

The experiment and the pretest both included a familiarization phase. For this phase, we designed a simplified map containing only four streets and four POIs. The subjects were encouraged to explore the familiarization map that was either presented as a paper or interactive version. All but one subject were already familiar with reading tactile paper maps. Thus, the familiarization phase for the braille map mainly served to ensure the subjects were aware of the symbols and textures used on our maps. The interactive map on the other hand was unknown for all users. They had to learn the double tap to activate the interactive elements and to become familiar with the speech output. Familiarization time was limited to 10 minutes but users were free to stop earlier if they felt comfortable with reading the map.

IV.2.3.3 Protocol

The experimental protocol included a short- and a long-term study that were each composed by two sessions (see Figure IV.3). There was a delay of one week between each of the four sessions, so that it took three weeks for each participant to complete the whole experiment.

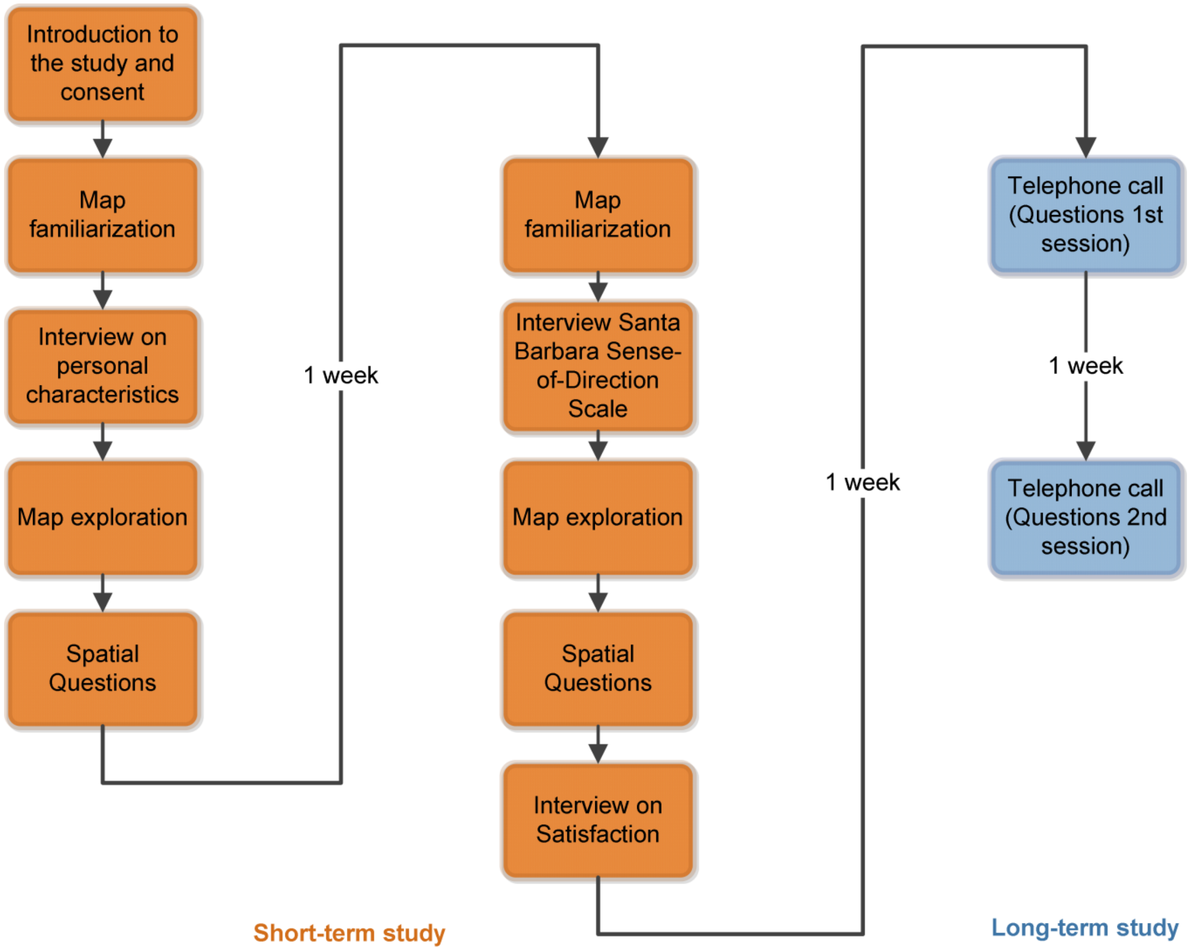


Figure IV.3: Experimental design of the study. The experiment was composed by a short-term and a long-term study. In the following the color code orange will be used for the short-term and blue for the long-term study.

IV.2.3.3.a Short-term Study: Comparing the Usability of Different Map Types

The first two sessions took place in the laboratory ULYSS, a dedicated experimental environment, in the IRIT research laboratory in Toulouse, France. Transport was organized door-to-door using the "Mobibus service", a local transportation service for people with special needs. Alternatively if participants preferred using public transport, they were picked up at the nearest metro or bus station and then accompanied to the laboratory. Video and sound files were recorded for both sessions after agreement from the participants. The mean duration of these sessions from arrival in the experimentation room to the end of the session (without waiting for transport) was 56.7 minutes (*SD* = 16.3). The minimum time was 30 minutes and the maximum time 103 minutes. There was no significant time difference between the two sessions. Both sessions were organized following a similar procedure. In the first session, the subjects explored the familiarization map. Following this, an interview on personal characteristics was conducted. Then, we asked subjects to explore and learn the first map (either IM or PM depending on the group) with both accuracy and time constraints ("as quickly and as accurate as possible"). Participants were informed that they would have to answer questions afterwards without having access to the map. In order to motivate them to memorize the map, we prepared a scenario: users were asked to prepare holidays in an unknown city and we invited them to memorize the map in order to fully enjoy the trip. Magliano et al. (1995) observed that subjects remember different types of map knowledge (landmark, route or survey knowledge) depending on the instruction given before exploration. Thus, in order to motivate users to memorize all types of spatial information, we did not provide any cue on the kind of map knowledge that they should retain. Subjects were free to explore until they felt like they had memorized the map. When they stopped, we measured the learning time and removed the map. Subjects then answered a questionnaire for assessing the three types of spatial learning (landmark, route, survey). The second session took place one week later and started with a familiarization phase followed by an interview on the Santa Barbara Sense of Direction Scale. The subjects then explored the second map type (either PM or IM depending on the group of subjects) and responded to the questions on spatial knowledge. We finally assessed their satisfaction regarding the two different map types.

IV.2.3.3.b Long-term Study: Investigating the Map Types' Impact On Spatial Memory

The aim of the long-term study was to observe how time would affect spatial learning and whether this depended on the map type. We made the assumptions that spatial scores and confidence would decrease over time as previous studies state that spatial knowledge diminishes over time (Downs & Stea, 1973). The long-term study, two telephone interviews, was done in continuity of the short-term study. The first phone call took place two weeks after exploration of the first map, and users were asked the same spatial questions as during the first session. The second phone call took place two weeks after the second map exploration, and users were asked the same questions as in this second session. Phone interviews lasted between 10 and 15 minutes.

IV.2.3.4 Observed Variables and Statistics

IV.2.3.4.a Independent variables

The principal independent variable in our study was the map type (within-participant factor). Participants were divided into two groups in which the order of presentation of the two map types was counterbalanced (PM first and then IM, and vice versa). The order of presentation was the second independent variable (between-participant factor). We did not expect the map content to have any effect on the results. Nevertheless, to assure correctness of the results, the order of presentation of the two different—but equivalent—map contents (1 and 2) was counterbalanced. The experience was therefore based on four groups with the following conditions: PM1-IM2, PM2-IM1, IM1-PM2, IM2-PM1. The third independent variable was the type of spatial knowledge—landmark, route and survey knowledge (Siegel & White, 1975)—as within-participant factor. For the long-term study the time was introduced as a within-participants factor.

IV.2.3.4.b Dependent variables

The three factors of usability were dependent variables: efficiency, effectiveness and satisfaction.

Efficiency

As stated before, efficiency is defined as the resources expended in relation to the accuracy and completeness with which users achieve goals. We measured efficiency as learning time, the time users needed for acquiring the map knowledge. Users were asked to "learn as quickly as possible" and therefore determined themselves when the learning process ended.

Effectiveness

Effectiveness—the accuracy and completeness with which users achieve specified goals—was measured as spatial knowledge acquired from map exploration. More specifically we wanted to assess the three types of spatial knowledge: landmark, route and survey (Siegel & White, 1975).

We have chosen tests for evaluating spatial cognition as has been discussed in subsection III.2.6.1. For assessing the landmark knowledge we asked participants to list the six street names (task called "L-S") and the six points of interest ("L-POI") presented on the map. The order of L-S and L-POI questions was counterbalanced across subjects. After completion of the landmark (L) related questions, we read out the complete list of streets and POI without giving any information concerning their locations on the map. This was to avoid that failures in the subsequent spatial tests (route and survey) were due to failures in short-term memory. Questions related to route (R) and survey (S) knowledge were each divided into three blocks of four questions. The order of presentation of the blocks was counterbalanced, but the order of the four questions within each block was maintained. Figure IV.4 depicts the structure of the questions.

Whereas survey knowledge is about the spatial relation between landmarks, landmark knowledge is about the landmarks as points of interest. We evaluated landmark knowledge with the recall of names of points of interest.

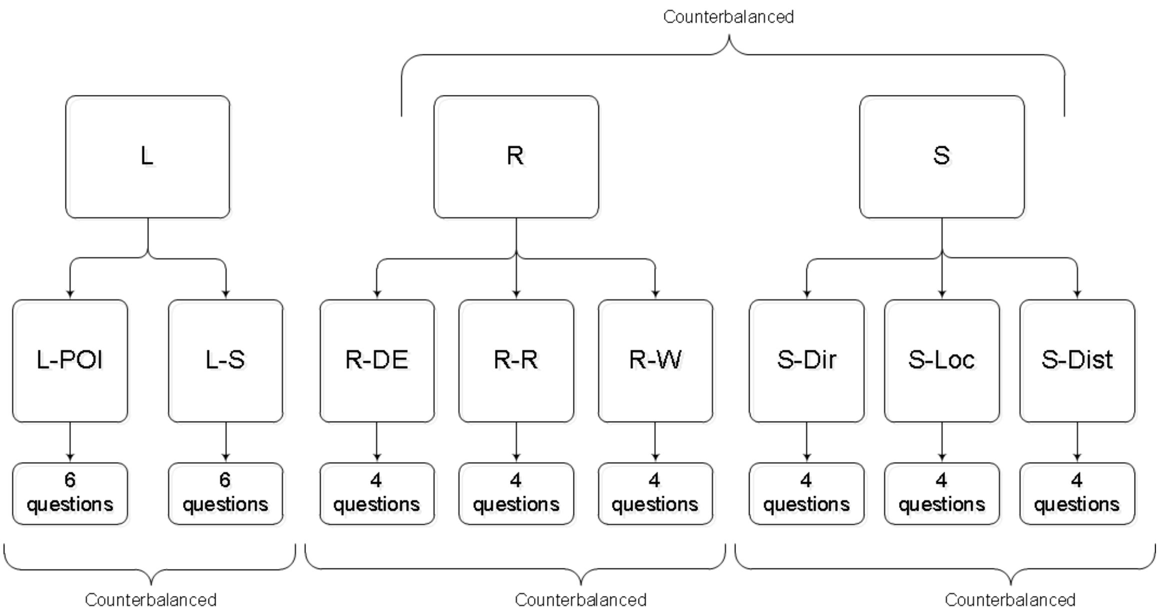


Figure IV.4 Structure of the spatial questions in the study. Questions were separated in three categories: landmark, route and survey. Within each category questions were counterbalanced. L = landmark, L-POI = landmark-points of interest, L-S = landmark - street names, R = route, R-DE = route distance estimation, R-R = route recognition, R-W = route wayfinding, S = survey, S-Dir = survey direction estimation, S-Loc = survey location estimation, S-Dist = survey distance estimation.

The three blocks for R type questions (containing each four questions) were: 1) Route distance estimation ("R-DE"): two pairs of POI were proposed (e.g. museum - spa vs. railway station - obelisk) and participants had to select the two points separated by the longest route when following the roads (also called functional distance in Ungar, 2000); 2) Route recognition ("R-R"): a route between two points was described and participants had to decide whether the description was correct or not; 3) Wayfinding ("R-W"): a starting point and a destination were provided. Then the participants had to describe the shortest route between these two points.

The three blocks for S type questions (containing each four questions) were: 1) Direction estimation ("S-Dir"): a starting point and a goal were given and participants had to indicate the direction to the goal using a clock system (e.g. three o'clock for direction east); 2) Location estimation ("S-Loc"): the map was divided into four equivalent parts (northeast, northwest, southeast, southwest), and participants had to decide for a map element in which part it was located; 3) Survey distance estimation ("S-Dist"): two couples of POI were proposed (e.g. museum - railway station vs. spa - obelisk), and participants had to decide which distance was the longest one in a straight line (Euclidian distance).

In the whole test each subject could get a maximum of 36 correct answers (12 for L, 12 for R and 12 for S). The set of questions can be found in the appendix VII.8.5.

Satisfaction

Satisfaction—positive attitudes towards the use of the product—was evaluated with quantitative (SUS) and qualitative questionnaires.

For using the SUS we replaced the usage of the word "cumbersome" with "awkward" to make question 8 of the SUS easier to understand (Bangor, Kortum, & Miller, 2008). In an earlier study we had observed negative reactions to question 7 which is entitled "I would imagine that most people would learn to use this product very quickly." Users had stated that "most people" would not use a product for visually impaired people. Therefore, we changed the wording to "I think that most visually impaired people would learn to use this product very quickly." We then translated the questionnaire into French (see appendix VII.8.3). As subjective questions we asked users which of the two map prototypes they had preferred and why.

Confidence

Finally, we introduced another set of dependent variables: the users' confidence in their responses to spatial questions. In the first presentation of an interactive map, Parkes (1988) had raised the question if access to an interactive map could increase users' confidence in map reading. Until today, this question has not been answered. Participants evaluated confidence on a scale from 1 (not confident at all) to 5 (very confident). The question was systematically asked after each of the eight blocks of spatial questions.

IV.3 Results

IV.3.1 Participants

We observed several personal characteristics including age, braille reading and reading of tactile images, use of new technologies and orientation skills. For the subjective estimation of these personal characteristics we used a scale of 1 (low) to 5 (high), except for age, Santa Barbara Sense of Direction Scale and Edinburgh Handedness Inventory.

All participants were braille readers as this was a crucial condition to participate in the study. Braille reading experience varied from five to 58 years (M = 32 years, SD =

14.8). Most subjects read braille bimanually. We also assessed frequency of braille reading (*M* = 4.5, *SD* = 1.1) as well as braille reading expertise (*M* = 4, *SD* = 1.0). The results show that the participants estimated themselves as experienced and frequent braille readers.

All users except one had prior experience in reading tactile images. The one user who did not have prior experience grew up in Morocco where the education system for visually impaired users differs from the French education system. We examined frequency of using tactile images (*M* = 2.2, *SD* = 1.2)—including figurative images, maps and diagrams—as well as expertise of reading tactile images (*M* = 3.3, *SD* = 1.1). Obviously users estimated themselves as less experienced in tactile image reading than in braille reading.

Most subjects were right-handed (19 participants who obtained scores between 23 and 30 in the Edinburgh Handedness Inventory); few were left-handed (three scores between 10 and 15) and few ambidextrous (two scores between 20 and 22).

Our study examined the usability of an interactive map which is based on innovative technologies. We were therefore interested in users' familiarity with new technology (*M* = 4.2, *SD* = 0.9) as well as users' expertise regarding new technology (*M* = 4, *SD* = 0.9). All participants had regular access to a computer and a cell phone. Most users also possessed an MP3 player.

As this study focuses on map learning, we were interested in participants' orientation skills. Scores from the Santa Barbara Sense of Direction Scale (converted back to a range from 1 to 7 for comparability with other studies) obtained a mean of 5.2 (*SD* = 0.6). We also interviewed users on travel frequency (M = 4.63, SD = 0.65) as well as their ease of travel (*M* = 4.13, *SD* = 0.85). Finally we let them estimate their sense of orientation (*M* = 4.38, *SD* = 0.77). This latter value evaluated the same skills as the SBSOD. By assessing both values, we wanted to compare whether users self-assessed values correlated with the results from the SBSOD.

IV.3.2 Short-term Study: Comparison of the Usability of Different Map Types

In the short-term study we made the assumptions that: 1/ exploration duration (corresponding to the learning time) reflects the efficiency of the maps; 2/ the quality of spatial learning (measured as spatial scores) reflects the effectiveness of the maps; 3/ the scores of an SUS questionnaire reflects user satisfaction. In addition, we also evaluated users' confidence in their responses, assuming a higher confidence for the interactive map. An alpha level of .05 was used for statistical significance in every test. Error bars in the diagrams indicate 95% confidence intervals.

IV.3.2.1 Learning Time (Efficiency)

During the experiment, users were asked to learn the map as accurately and as quickly as possible. Efficiency was measured as the time participants needed to memorize the map content (Learning Time). Participants decided when they felt ready to end the learning phase.

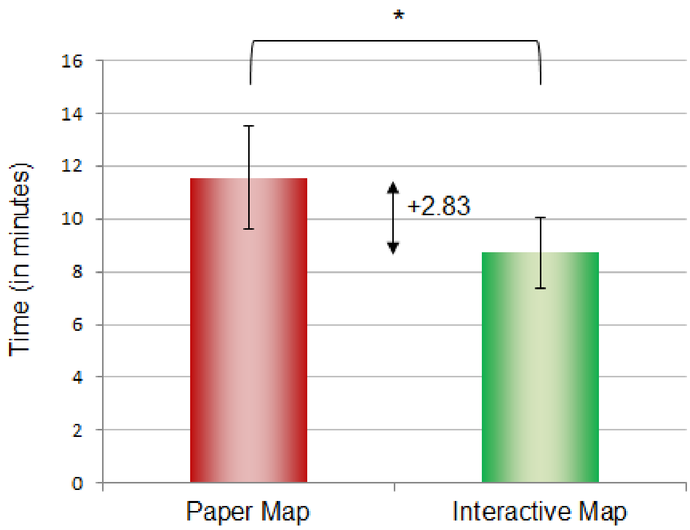


Figure IV.5: Learning Time (mean values measured in minutes) for the paper map (left) as compared to the interactive map (right). The Learning Time for the interactive map was significantly lower than for the paper map (lower is better). In other words, efficiency of the interactive map was significantly higher. Error bars show 95% confidence intervals in this and all following figures. * p < .05. In the remainder of this chapter we will use the color code red for the paper map and green for the interactive map.

Learning Time varied from five to 24 minutes with a mean value of 10.1 (*SD* = 4.4). The observed time values were not normally distributed (Shapiro-Wilk W = 0.89, p < .001) but logarithms conformed to a normal distribution (Shapiro-Wilk W = 0.96, p = .086). The logarithm of Learning Time was then compared across map type and order of map presentation in a 2 (map type, within-participants factor) x 2 (order of presentation, between-participants factor) analysis of variance (ANOVA). A significant effect of the map type emerged ($F(1,22) = 4.59$, $p = .04$) as depicted in Figure IV.5. Learning Time was significantly shorter for the interactive map (*M* = 8.71, *SD* = 3.36) than for the paper map (*M* = 11.54, *SD* = 4.88). We did not observe any effect of the order of presentation ($F(22,1) = 0.24$, $p = .63$). Finally, there were no significant interactions between variables. We verified that there was no learning effect between the first and the second map that subjects explored. We also verified that there was no significant difference between the two different map contents.

IV.3.2.2 Spatial Learning (Effectiveness)

In order to evaluate spatial learning we analyzed the scores for the questions on spatial knowledge. We expected that participants would obtain higher scores of spatial knowledge with the interactive map than with the paper map.

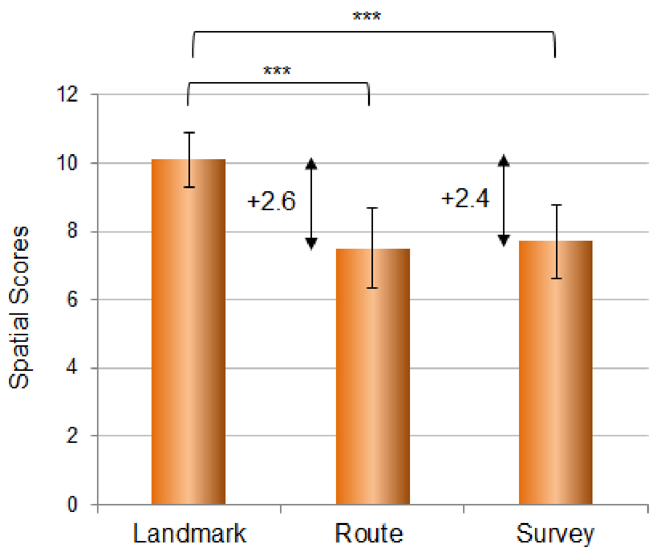


Figure IV.6: Mean spatial scores for responses to landmark, route and survey questions (paper and interactive map summed up). Mean scores for the landmark tasks were significantly higher than those for the route and survey tasks. There was no significant difference between R and S questions. *** p< .001

The sums of the scores (i.e., L, R and S tasks summed up for each map) varied from eight to 36 and were distributed normally (Shapiro Wilk W = 0.96, p = .089). They were compared across map type and order of map presentation in a 2 (map type) x 2 (order of presentation) analysis of variance. Although the scores for the interactive map were slightly higher (*M*=25.6, *SD* = 6.8) than for the paper map (*M* = 24.9, *SD* = 6.8), the effect of map type was not significant (F(22,1) = 0.45, p = .51). There was no effect of the order of presentation (F(22,1) = 0.08, p = .79). We did not observe any significant interaction either (F(22,1) = 1.25, p = .28). We verified that there was no learning effect between the first and the second map that subjects explored. We also verified that there was no significant effect between the two different map contents.

However, differences were observed when looking at individual scores for L, R, and S questions (see Figure IV.6). Pairwise Wilcoxon rank sum tests with Bonferroni correction (alpha level = .017) revealed that the difference between L (*M* = 10.1, *SD* = 2.0) and R (*M* = 7.5, *SD* = 2.9) was significant (N = 45, Z = 5.20, $p < .001$) as well as the difference between L and S (*M* = 7.7, *SD* = 2.7) questions (N = 43, Z = 5.06, $p < .001$). There was no significant difference between R and S questions (N = 41, Z = 0.41, $p = .68$).

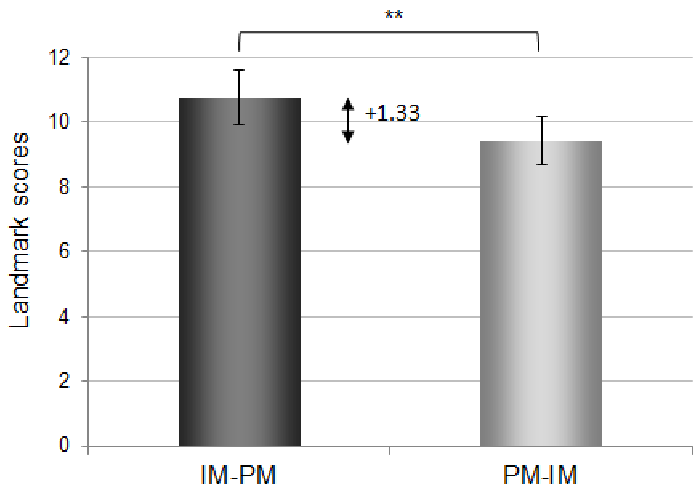
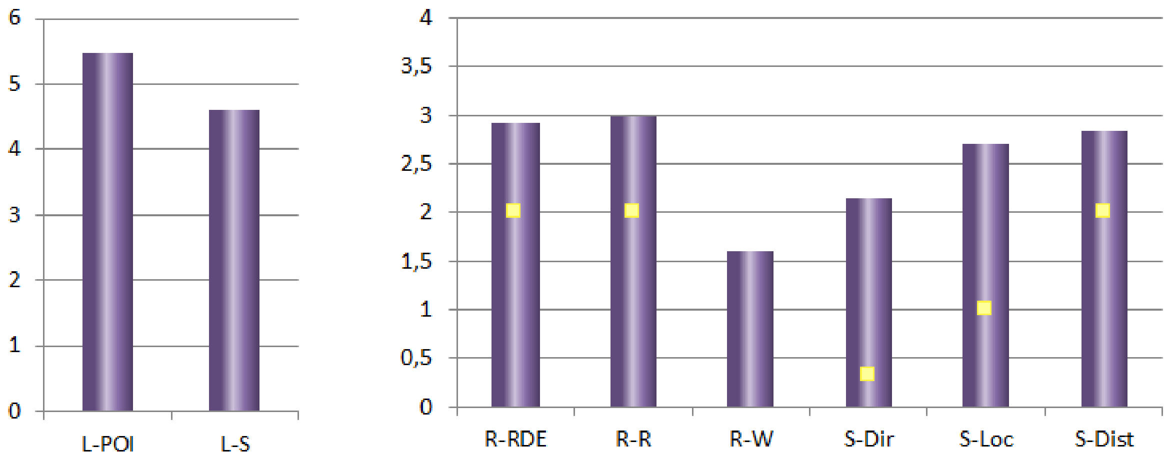


Figure IV.7: Effect of order of presentation on landmark scores. The mean scores for L questions were significantly higher when the interactive map was presented before the paper map. ** p < .01

Finally, we analyzed interactions between individual scores and other variables. Mann-Whitney U Test revealed a significant effect of the order of map presentation on L scores (U = 149, n1 = n2 = 24, $p = .004$). Figure IV.7 shows that L scores were higher if the interactive map was presented before the paper map (*M* = 10.75, *SD* = 2.07) than in the reversed order (*M* = 9.42, *SD* = 1.82). There was no significant effect of order of presentation for R and S scores.

We also verified for each spatial test that results were above the level of chance (see Figure IV.8). Tests L-POI (mean = 5.48) and L-S (mean = 4.6) concerned the recall of names. Coming up with the correct names cannot be done randomly and therefore the chance level was zero for both tests. In R-RDE users had to choose which one out of two itineraries was longer. There was a chance of 50% to guess the correct answer. Out of a maximum of 4 points, the chance level was thus 2 points. The mean value was above chance level. Mann-Whitney U Test revealed a significant difference between obtained scores (mean = 2.92) and chance level (U = 384, n1 = n2 = 48, $p < .001$). In R-R tests, users had to identify whether a proposed itinerary was true or false. Again, there was a chance of 50% to guess the correct answer, thus 2 out of 4 points. The mean value (mean = 2.98) was above chance level. Mann-Whitney U Test revealed a significant difference between obtained scores and chance level (U = 576, n1 = n2 = 48, $p < .001$). In R-W tests, users had to name the streets that composed a certain itinerary, without knowing how many streets composed this itinerary. There was almost zero chance to guess the number and correct names of streets (mean = 1.6). In S-Dir Tests users had to choose a direction following the clock method. As there are twelve possible timings (we did not accept anything more precise than one hour difference), the chance of guessing correctly was 1/12 (=0.083). The mean value (mean = 2.15) was above chance level. Mann-Whitney U Test revealed a significant difference between obtained scores and chance level ($U = 240$, $n1 = n2 = 48$, $p < .001$). In the S-Loc test users had to guess in which one out of four possibilities a point of interest was situated. Therefore there was a chance of 25% for random guessing, i.e. 1 out of 4 points maximum. The mean value (mean = 2.7) was above chance level. Mann-Whitney U Test revealed a significant difference between obtained scores and chance level ($U = 384$, $n1 = n2 = 48$, $p < .001$). Finally, for the S-Dist test, users had to guess which one of two trajectories was the longer one. There was 50% random chance, i.e. two out of four points maximum. The mean value (mean = 2.83) was above chance level. Mann-Whitney U Test revealed a significant difference between obtained scores and chance level ($U = 480$, $n1 = n2 = 48$, $p < .001$).



(a)

(b)

Figure IV.8: Mean value (violet bar) and chance level (yellow box) for each spatial cognition test. If no yellow box is reported, the chance level is equivalent to 0. (a) L Scores have maximum values of 6, (b) R and S scores have maximum values of 4.

IV.3.2.3 User Satisfaction

We predicted that the interactive map would yield higher satisfaction, i.e. comfort and positive attitudes towards the use of the map, than the paper map. User satisfaction was assessed with the standardized SUS questionnaire (Brooke, 1996) translated into

French. In addition to these quantitative results, we also recorded qualitative comments from the users.

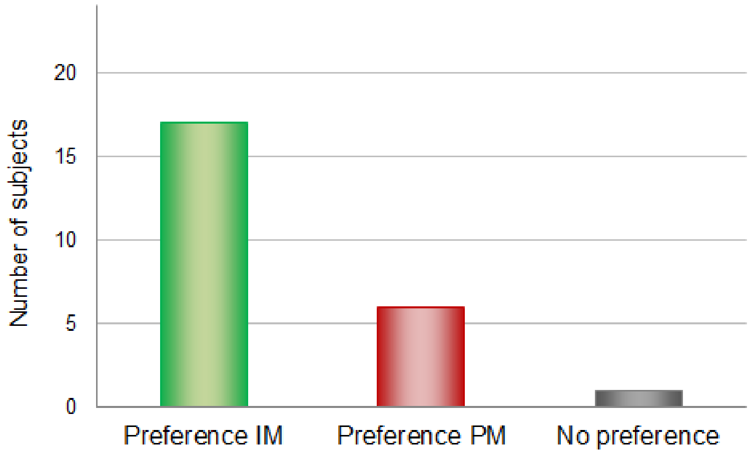


Figure IV.9: For each map type the number of participants who preferred this map type over the other is reported. One user had no preference.

The SUS questionnaire provides scores between 0 and 100. In our study SUS scores taken altogether for both maps varied between 45 and 100 with a mean value of 83.8 (SD = 13.9). Scores were not normally distributed (Shapiro Wilk W = 0.85, $p < .001$). They were marginally better for the interactive map (M = 86.6, SD = 13.7) than for the paper map (M = 81.0, SD = 13.9), without being statistically significant (Wilcoxon signed-rank test, N = 22, Z = 1.9, p = .058). Yet, when asked which map they preferred, more users answered in favor of the interactive map (Figure IV.9). Of a total of 24 users, six users preferred the paper map, 17 preferred the interactive map and one had no preference.

Most users quickly learnt the double-tap, whereas the user who gave a SUS score of 45 encountered problems using the double-tap. This user (female, aged 64) possessed prior experience with paper maps with braille legends and almost 60 years of experience in braille reading. She mentioned that she enjoys reading braille and that she had been surprised by the usage of an interactive map.

The six users who preferred the paper map were interviewed about which aspect they had most liked or disliked about the map. Two users stated the ease of memorizing written information. One user mentioned interaction problems with the interactive map, more precisely that there was too much audio output. One user stated that she preferred braille over speech, while another one mentioned the ease of use. Finally one user said that the legend of the paper map was helpful because it presents a list of all the map elements that the user should find during exploration.

We asked the 17 users who preferred the interactive maps which aspect they had most liked or disliked about the map. Seven users preferred speech output over braille text. Four users enjoyed that there was no need to read a legend. Three users enjoyed the ease of use of the interactive map. One user stated the ease of memorizing spoken text; one user said that the interactive map was ludic. Finally one user stated the possibility to add supplementary content (like opening hours) on the interactive map without overloading the tactile drawing. This would not be possible on a raised-line map with braille where the amount of information is limited through the available space.

During the discussion after the interviews, users mentioned other explanations for their preferences. Some users who preferred the tactile map stated that the tactile map with braille can be more easily transported and that the tactile map was cheaper in terms of production. Also, one user liked that the paper map gave access to the spelling of a word. On the other hand, several users stated that the interactive map was quicker to read, and some also mention that it was quicker to memorize. Interestingly several users with good braille reading skills stated that the interactive map would be interesting for someone who does not read braille. One user preferred the interactive map because it feels less like assistive technology than the tactile map with braille. Finally, several users mentioned that they had been surprised by the novelty of the interactive map.

IV.3.2.4 Users' Confidence

We expected higher confidence of users in their responses when using the interactive map than when using the paper map. Users' confidence in response to spatial questions for the paper map varied from 1.83 to 4.67 with a mean value of 3.87 (SD = 0.68). For the interactive map the values varied from 2.5 to 5.00 with a mean of 3.98 (SD = 0.59). As scores for users' confidence were not normally distributed (Shapiro Wilk W = 0.89, $p < .001$), we used non-parametric tests. There was no significant effect on users' confidence in their responses to spatial questions as regards to the map type (Wilcoxon signed rank, $N = 22$, $Z = 0.84$, $p = .4$) or the order of presentation (Mann-Whitney U Test, $U = 71.5$, n1=n2=12, $p = 1.0$). Our hypothesis was therefore not confirmed.

However, we observed a significant effect on users' confidence according to the type of task—landmark ($M = 10.1$, $SD = 2.0$), route ($M = 7.5$, $SD = 2.9$), or survey ($M = 7.7$, $SD = 2.7$) questions—as shown in Figure IV.10. Confidence was significantly higher after Bonferroni correction (alpha level = .017) for L than R (Wilcoxon signed-rank tests, N = 46, Z = 5.89, $p < .001$) or S (N = 44, Z = 5.75, $p < .001$) questions. Moreover, the figure reveals a similar distribution of mean confidence and mean spatial scores. No significant difference emerged between confidence concerning R and S tasks (N = 39, Z = 1.56, *p* = .12). We did not observe any significant interaction.

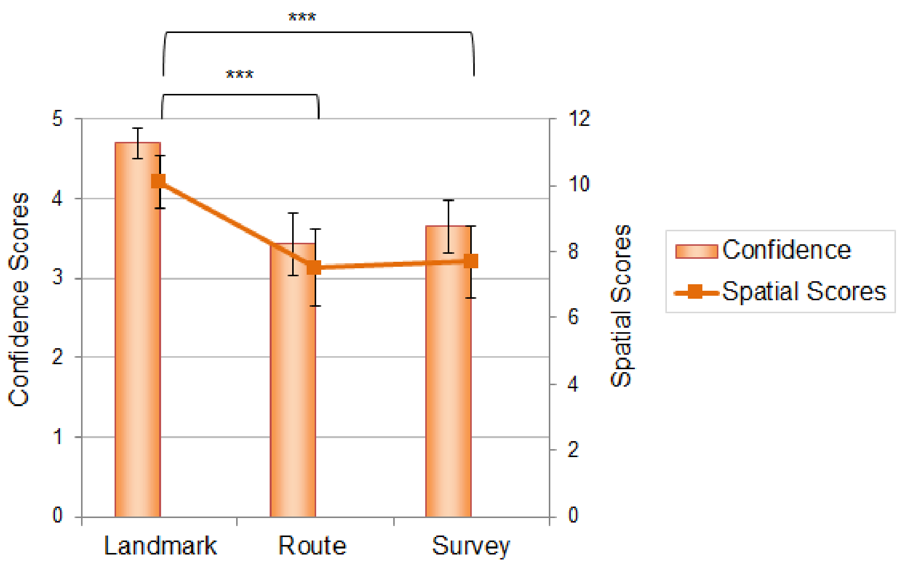


Figure IV.10: Mean spatial scores (depicted as graphs, right axis) and mean confidence (depicted as bar chart, left axis) for responses to landmark, route and survey questions (paper and interactive map summed up). Mean scores for the landmark tasks were significantly higher than those for the route and survey tasks. There was no significant difference between R and S questions. Confidence was significantly higher for L than for R or S questions. Besides, the figure reveals a similar distribution of mean confidence and mean spatial scores. *** p< .001

IV.3.2.5 Correlations

We analyzed linear correlations between users' personal characteristics and dependent variables. Figure IV.11 illustrates the many significant correlations. In order to facilitate the visualization of correlations we divided the values in three groups: age-related factors, other personal characteristics and dependent variables. In this subsection we only discuss relevant correlations.

We observed various correlations between different age-related and personal factors. Some of these correlations were expected. For instance, the number of years of braille reading (Braille_years) was strongly correlated to proportion of lifetime with blindness (p_lifetime_blind, r = .63, p = .001), meaning that people who have been blind for a longer period of their lives have also been braille readers for a longer time. Santa Barbara Sense of Direction Scale (SBSOD) and the self-reported judgment of sense of orientation (SenseOfOrientation) were correlated (r = .57, p = .004) skills. The latter is also correlated with expertise in reading tactile images (TactileImage_exp, r = .67, p < .001), which includes tactile maps. These measures all refer to similar skills. Other correlations were more surprising. Expertise in using new technologies (NewTech_exp) was correlated with results from the SBSOD (r = .47, p = .02), meaning that people with better orientation skills were more experienced in using technology and vice versa. Ease of travel (Travel_ease) was negatively correlated with proportion of lifetime with blindness (r = -.44, p = .032) and age (r = -.43, p = .035), meaning that older and early blind people faced more apprehension towards traveling. Proportion of lifetime with blindness was also correlated with the frequency of using new technology (NewTech_freq, r = .47, p = .02), meaning that early blind people were frequent users of new technology.

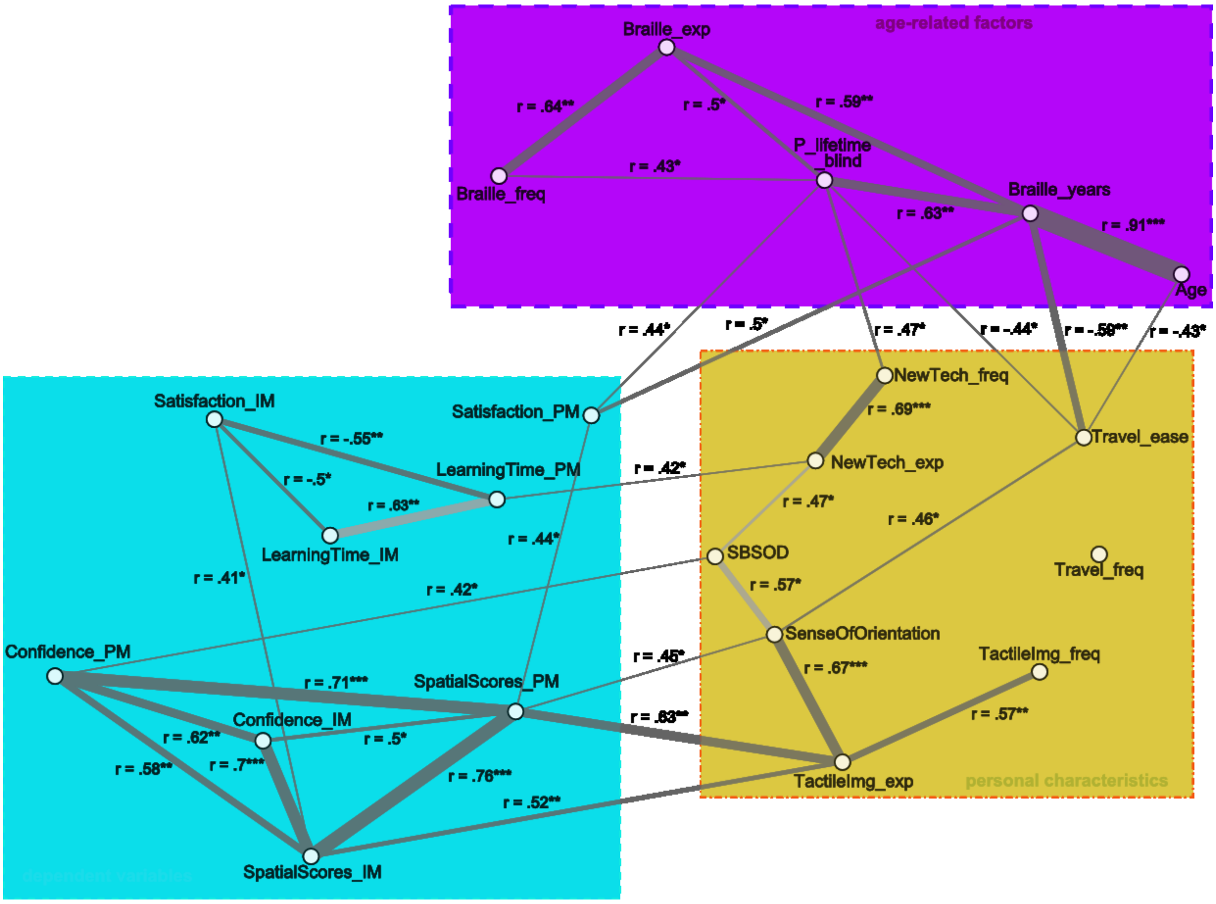


Figure IV.11: Significant correlations for dependent variables, age-related factors and personal characteristics. The size of the lines between nodes increases with the strength of the correlation (r value). Nodes have been manually positioned for better readability. Abbreviations: exp = expertise, freq = frequency, IM = interactive map, PM = paper map, SBSOD = Santa Barbara Sense of Direction Scale. * p < .05, ** p < .01, *** p < .001. The diagram was created with the Gephi software (Bastian, Heymann, & Jacomy, 2009).

Multiple correlations also existed when looking at dependent variables. As we expected from the observation in Figure IV.11, effectiveness (total result to L, R, and S tasks) of paper map exploration (SpatialScores_PM) was correlated with users' confidence in using paper maps (Confidence_PM, r = .71, p < .001); effectiveness of interactive map exploration (SpatialScores_IM) was correlated with users' confidence in using interactive maps (Confidence_IM, $r = .7$, $p < .001$). Similarly, effectiveness and satisfaction of using paper maps (Satisfaction_PM) were correlated ($r = .44$, $p = .033$), as well as effectiveness and satisfaction of using interactive maps (Satisfaction_IM, $r = .41$, $p = .044$). High performers perceived a higher satisfaction than low performers. The satisfaction also depended on efficiency: satisfaction for the interactive maps was negatively correlated with the learning times both for paper maps (LearningTime_PM, $r = -.55$, $p = .005$) and interactive maps (LearningTime_IM, $r = -.5$, $p = .13$). Both learning times were correlated ($r = .63$, $p = .001$).

Interesting correlations also emerged between dependent variables and users' characteristics. The learning time for the paper map was correlated with the expertise in using new technology ($r = .42$, $p = .042$). In other words subjects that were expert users of new technology needed more time for reading the paper map with braille text. The effectiveness of reading the paper map was correlated with the expertise in reading tactile images ($r = .63$, $p = .001$); as was the effectiveness of reading interactive maps with the expertise in reading tactile images ($r = .52$, $p = .009$). This is not surprising as both map types are based on exploring a raised-line map overlay. The effectiveness of reading the paper map was correlated with the sense of orientation ($r = .45$, $p = .029$), so users with a better sense of orientation obtained higher spatial scores. Users' confidence with the paper map was correlated with SBSOD scores ($r = .42$, $p = .039$), meaning that users who scored themselves higher in the SBSOD questionnaire were more confident regarding their responses to spatial questions. Finally, the satisfaction of reading paper maps was correlated with the proportion of lifetime without blindness ($r = .44$, $p = .031$) and the braille reading experience ($r = .5$, $p = .014$), meaning that early blind and better braille readers experienced a higher satisfaction towards reading the paper map.

In a more detailed analysis, we looked at correlations between individual characteristics and the scores for the different types of spatial knowledge (landmark, route and survey). Travel frequency was negatively correlated with scores for survey knowledge on the paper map ($r = -.47$, $p = .02$), meaning that people who travel more frequently obtained lower scores in the survey questions. Landmark knowledge for the paper map was correlated both with the sense of orientation ($r = .55$, $p = .005$) and the Santa Barbara Sense of Direction Scale ($r = .56$, $p = .004$), meaning that people with higher orientation skills obtained better landmark scores. In the same way, landmark knowledge for the interactive map was correlated with the sense of orientation ($p = .63$, $p = 0.001$) and the Santa Barbara Sense of Direction Scale ($r = .53$, $p = .007$).

IV.3.3 Long-term Recall: Comparison of the Effectiveness of the Interactive and Paper Maps

The aim of the long-term study was to observe how time would affect spatial learning and whether this depended on the map type. We made the assumptions that spatial scores and confidence would decrease over time. As short-term results showed that the interactive map was more efficient in spatial learning, we expected a less important decrease with the interactive map than with the paper map. An alpha level of .05 was used for statistical significance in every test.

IV.3.3.1 Long-term Recall of Spatial Information

After a two week delay users were asked exactly the same questions related to spatial knowledge. Hence, we were able to directly compare results between the immediate (short-term) and delayed (long-term) questions.

A main effect of time clearly emerged (Wilcoxon signed rank, $N = 45$, $Z = 5.84$, $p < .001$). Short-term scores for both maps varied from 8 to 36 with a mean of 25.75 (SD = 6.55). Long-term scores varied from 0 to 35 with a mean of 15.73 (SD = 8.35). The long-term scores for the paper map varied between 4 and 34 with a mean value of 16.54 (SD = 7.99). For the interactive map spatial scores varied between 0 and 35 with a mean value of 14.92 (SD = 8.78). These values were not distributed normally (Shapiro-Wilk $W = 0.92$, $p = .004$). Although the mean score for the paper map was slightly higher, there was no significant effect of the map type (Wilcoxon signed rank test, $N = 24$, $Z = 0.96$, $p = .34$). There was no effect of order of presentation of maps on long-term scores (Mann-Whitney U test, $U = 226.5$, $n1 = n2 = 24$, $p = .21$). We did not observe any significant interactions.

As for the short-term results, differences were observed when looking at individual scores for L, R, and S tasks (see Figure IV.12). At long-term scores for L questions had a mean of 4.71 (SD = 3.64), scores for R questions had a mean of 4.96 (SD = 2.68) and scores for S questions a mean of 6.06 (SD = 3.14). Pairwise Wilcoxon rank sum tests with Bonferroni correction (alpha level = .017) revealed a significant difference between L and S scores ($N = 40$, $Z = 4.95$, $p < .001$) with the S scores being superior. Neither the difference between L and R scores was significant ($N = 43$, $Z = 1.00$, $p = .32$), nor the difference between R and S scores ($N = 41$, $Z = 0.41$, $p = .68$).

Figure IV.12 shows a comparison between scores for L, R and S questions at short- and long-term. We observed a significant effect of time on each spatial task. Short-term scores for L questions corresponded to 84% of the maximum score (M = 10.08, SD = 2.04) and long-term scores corresponded to 39% of the maximum score (M = 4.71, SD = 3.64). The decrease was 45%. A Wilcoxon rank signed test revealed a significant difference (N

= 42, Z = 5.65, p < .001). R scores corresponded to 62 % (*M* = 7.5, *SD* = 2.91) at short-term and 41% (*M* = 4.96, *SD* = 2.68) at long-term, which corresponds to a 21% decrease. A Wilcoxon rank signed test revealed a significant difference (N = 42, Z = 4.72, p < .001). Finally, S scores corresponded to 64% (*M* = 7.69, *SD* = 2.72) at short-term and 51% (*M* = 6.06, *SD* = 3.14) at long-term, a significant 13% decrease (Wilcoxon, N = 38, Z = 3.99, p < .001).

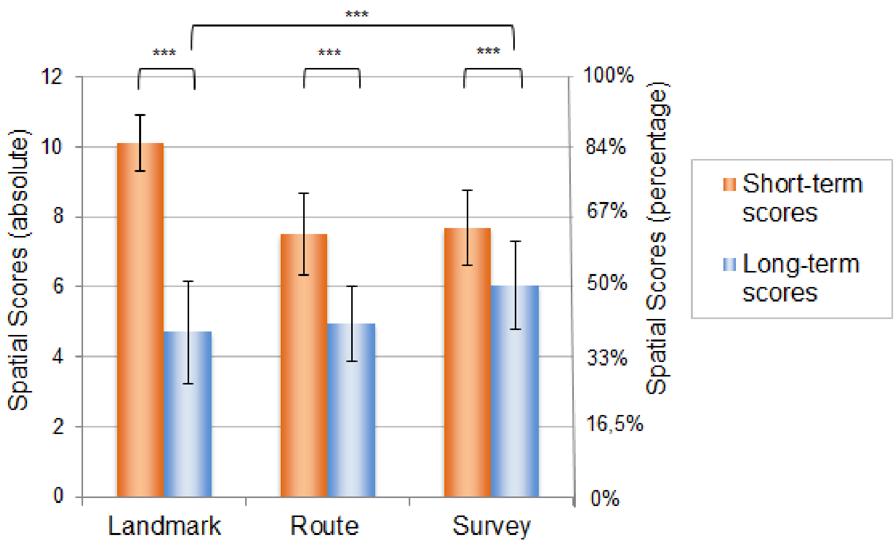


Figure IV.12: Mean scores for landmark, route and survey responses at short-term (immediate) and long-term (delayed). A significant effect of time is observed: all scores were lower two weeks after exposure. The difference was most important for landmark scores. The right axis depicts the percentage of the scores. LT: long-term, ST: short-term, *** p < .001.

IV.3.3.2 Users' Confidence at Long-Term

For the paper map, users' confidence in their own responses to delayed spatial questions varied from 1 to 4.33 with a mean of 2.66 (*SD* = 0.99). For the interactive map these values varied from 1 to 4.06 with a mean of 2.62 (*SD* = 0.99). Scores for users' confidence were not normally distributed (Shapiro Wilk W = 0.95, p = .042). There was no significant effect on users' confidence related to the map type (Wilcoxon signed rank, N = 23, Z = 0.87, p = .39). There was no effect of the order of presentation (Mann-Whitney U Test, U = 267, n1 = n2 = 24, p = .67). A main effect of time clearly emerged (Wilcoxon signed rank test, N = 48, Z = 5.98, p < .001) with short-term scores being superior.

As depicted in Figure IV.13 we observed a significant effect of task (L, R, or S questions) on users' confidence. At long-term, confidence in L questions had a mean of 2.93 (*SD* = 1.34), confidence in R questions had a mean of 2.32 (*SD* = 1.04), confidence in S questions had a mean of 2.67 (*SD* = 1.01). After Bonferroni correction (alpha level = 0.017), confidence was significantly higher for L than R (Wilcoxon signed-rank tests, N =

42, Z = 3.25, p = .001). The difference between R and S scores was also significant (N = 35, Z = 3.01, p = .003). There was no significant difference between L and S scores (N = 41, Z = 1.67, p = .09). In addition, there was a significant effect of time on each score (Figure IV.13), with short-term scores being higher for L task (Wilcoxon signed rank test, N = 43, Z = 5.71, p < .001), R task (N = 44, Z = 5.43, p < .001) and S task (N = 45, Z = 4.87, p < .001).

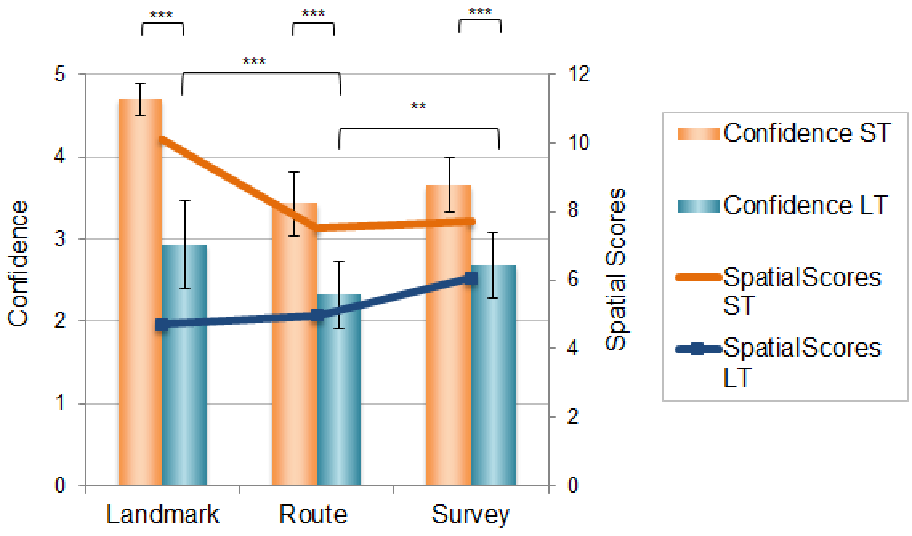


Figure IV.13: Mean confidence (left y-axis) for landmark, route and survey knowledge summed up for the paper and the interactive map both at short- and at long-term. A significant effect of time is observed: confidence is lower two weeks after map exploration. The difference is most important for landmark questions. Besides, the figure reveals a strong correlation between confidence and spatial scores (orange) at short-term but not at long-term (blue). The right axis applies to spatial scores. Abbreviations: ST = short-term, LT = long-term. ** p < .01, *** p < .001.

IV.4 Discussion

IV.4.1 Comparing Usability of a Paper and an Interactive Map

Learning time was significantly shorter for the interactive map. Yet, learning times for both map types were strongly correlated. The correlation is not surprising as in both cases the same tactile map overlay was used. We assume that the motor strategies used to explore the map per se were the same for both map types. The longer learning time observed with the paper map certainly lies in the way information was retrieved. For the interactive map, speech output is obtained immediately during map exploration with a double tap on interactive elements. On the paper map many additional actions were required to obtain the same information. First users had to read and memorize the abbreviation, then move at least one hand to the legend, find the abbreviation in the list, read the explanation, and finally move the hand back to the map. This referencing between the map and the legend is time consuming and disrupts the map reading process (Hinton, 1993). Similarly, Wang et al. (2012) observed that most users were quicker using and interactive map than a tactile paper map, as they could identify map locations more easily.

Yet, not all studies comparing an interactive prototype with a tactile diagram demonstrate an advantage for the interactive device. Giudice et al. (2012) compared a vibro-audio tablet interface against a hardcopy tactile stimuli for learning non-visual graphical information, both with blind and blindfolded participants. The vibro-audio tablet interface synchronously triggered vibration patterns and auditory information when the users touched an on-screen element. The hardcopy tactile graphics were embossed and did not offer any additional feedback than the embossed relief. They observed that learning time with the interactive prototype was up to four times longer than with the paper diagram. Giudice et al. suggested that lines and curves are harder to perceive when indicated by vibrations than when printed in relief. Obviously, because of the presence of the embossed map in our interactive map prototype, we did not face the same issue in this study. However, learning time with the interactive map is significantly shorter than with the paper map. It clearly shows that reading the interactive map—composed by the raised-line map and audio information—is more efficient and does not rely on additional training.

We were expecting better spatial scores (improved effectiveness) for the interactive map prototype. Our expectation was that the decrease in efficiency of the paper map and the disruption between map reading and reading the legend, might have negative consequences on the effectiveness of the paper map. The absence of a significant effect in our study is probably related to the small number of elements that were presented on the maps. A greater complexity might have led to different results. Indeed, the readability and thus the effectiveness of a tactile map is impaired if the map contains a great number of elements and legends (Tatham, 1991). In contrast, it is possible to present a richer and more complex content with an interactive map (Hinton, 1993). As the amount of spatial information in the maps that we used was voluntarily limited, it would be interesting to design an ad-hoc experiment comparing raised-line and interactive maps containing greater spatial information, such as a complex neighborhood or city. We will have a more detailed look on spatial cognition in the following subsection.

We observed a better satisfaction for the interactive map with 17 out of 24 users stating that they preferred the interactive map. The three most cited reasons are the use of speech output instead of braille, the fact that there is no legend, and finally the ease of using the prototype. Bangor et al. (2008) proposed a description that correlates with a given score. Scores of 100 are "best imaginable", around 85 "excellent", around 73 "good", around 52 "OK", around 38 "poor" and below 25 "worst imaginable". In our study mean SUS scores for both map types were in the range of "excellent" scores. This is not surprising as both maps were simple maps with few details, and thus rather easy to read. In addition, our users evaluated themselves as experienced in mobility and orientation and expressed their interest in map reading. Except one participant, all had prior experience in reading tactile maps. Bangor et al. also associated ranges of acceptability with SUS scores. Scores above 70 were classified as acceptable, scores between 50 and 70 as marginally acceptable and scores below 50 as unacceptable. Specifically looking at the satisfaction for the paper map, 18 scores were in the range of acceptable and six scores in the range of marginally acceptable (varying from 52.5 to 70). Concerning the interactive map, 21 scores were in the range of acceptable, two in the range of marginally acceptable (57.5 respectively 67.5) and one in the range of unacceptable (45). Bangor et al. stated that SUS scores were sometimes related to participants' performance (meaning that low performers gave low SUS scores and high performers gave high SUS scores). This is probably the explanation for some of the low SUS scores observed in our experiment. Indeed, the only participant without prior map reading experience scored both maps in the range of marginally acceptable. Most probably, map reading was more difficult for him than for other participants in the study, and he simply did not enjoy exploring maps in general. The participant who gave the lowest score (45) for the interactive map gave a high score for the paper map (90). This user (female, aged 64) possessed almost 60 years of experience in braille reading. She described herself as a very frequent braille reader with extremely good braille reading skills. She had been visually impaired since birth. We suppose that her above-average braille experience and reading skills as well as the high proportion of lifetime with visual impairment were the reasons why she clearly preferred the tactile paper map (Brock, Truillet, et al., 2012). This explanation is supported by the fact that, for all users, SUS scores for the paper map were positively correlated with braille reading experience as well as the proportion of lifetime with visual impairment. SUS scores for the interactive map were not correlated with braille reading experience or any age-related factor. This means that interactive maps are perceived as accessible even for participants with low braille reading skills. We confirmed this assumption with a blind person not included in the user group of this study. This blind person was 84 years old and had lost sight when he was 66 years old. He learnt braille lately and had limited braille reading skills. A standard raised-line map with braille text was not accessible for him, unless we printed the braille with large spacing between letters. Contrary, he could immediately use the interactive map and gave an excellent score of 87.5 points in the SUS questionnaire. The interactive map provided him with access to spatial information that he could not have obtained with a regular paper map.

We found further correlations between satisfaction and dependent variables. Unsurprisingly, satisfaction with the paper map is correlated with effectiveness (spatial learning scores). This means that more successful users experienced higher satisfaction while using the map. Satisfaction with the interactive map is positively correlated with users' confidence in their responses, and negatively correlated with learning time for both maps. These different correlations show that the satisfaction is indeed related to the amount of information that users can retrieve from the map they are exploring and the time needed for this task. The fact that users need less time to retrieve spatial information from a multimodal interactive map is an important component of satisfaction.

IV.4.2 Spatial Cognition in the Blind

In this study, effectiveness—one of the three dimensions of usability—has been measured as spatial learning scores. It is interesting to look more closely at these scores as they can help us understand how visually impaired people acquire spatial knowledge from interactive maps. It is commonly accepted to divide spatial knowledge in three dimensions: landmark, route and survey (L, R, S) knowledge (Siegel & White, 1975). Routes are constructed by linking different landmarks through direct exploration. After exposure to many routes which can be interconnected, a person is able to generate a mental map of the explored environment, i.e. survey knowledge. This theory served as a frame of reference in many studies of spatial cognition. In our study we assessed the effect of the map type on the learning of the different components (landmark, route and survey) of spatial knowledge. We looked at this effect immediately after map exploration and with a two week delay.

IV.4.2.1 Spatial Memory Following Haptic Map Exploration

As discussed before, our expectation of better spatial learning with the interactive map as compared to the paper map was not confirmed. More precisely, there was no significant difference between scores obtained with the interactive or the paper map, neither at short-term nor at long-term. Differences emerged when we looked at the different types of spatial knowledge: landmark, route and survey knowledge.

IV.4.2.1.a Short-Term Spatial Memory

We observed that landmark knowledge shortly after exploration was significantly superior to route and survey knowledge. There was no significant difference between R and S scores. Although it applies to map exploration and not to pedestrian navigation, this result is consistent with Magliano et al. (1995) who suggested that the acquisition of route and survey knowledge depended on the previous acquisition of landmark knowledge. As we did not observe a significant difference between route and survey knowledge, our results are in contrast with Thorndyke and Hayes-Roth (1982) who observed that, when exploring a map, subjects would acquire survey knowledge rather than route knowledge. This difference may be related to the specificity of blind users that preferentially encode the location of selected landmarks (Thinus-Blanc & Gaunet, 1997). Indeed, these landmarks may be used later to mentally select routes, and confirm one's own position during travel. This process is generally favored because of two main reasons: first, visually impaired users do not have easy access to maps; second, they are taught to use route descriptions during mobility and orientation training. However, it appears from our results that there is a better recall of landmarks than routes. Although it may be surprising at first glance, it is not. Landmarks are the initial elements that allow route construction.

IV.4.2.1.b Long-Term Spatial Memory

The aim of the long-term study was to observe how time would affect spatial memory. Previous studies demonstrated a decrease in precision of spatial information in long-term memory (Downs & Stea, 1973; Giudice et al., 2013). Consequently, we expected that spatial scores would decrease over time. This hypothesis was confirmed as L, R and S scores decreased two weeks after exposure. The decrease, however, was not uniform for the three types of spatial knowledge. Interestingly L scores were superior to R and S scores immediately after exploration. Two weeks later, this difference not only disappeared but was inverted with S scores being significantly more important than L scores. Looking at details, the decrease was more important for landmark (45%) than for route (21%) or survey knowledge (13%). This result confirms that landmarks are useful to build route and survey knowledge during haptic exploration of a map. It also shows that route and survey knowledge is more robust, and does not rely on an accurate and extensive memorization of all landmarks. This is in line with the observation that spatial short-term memory is organized in an ego-centric representation, whereas spatial long-term memory is rather organized in an allocentric representation (Giudice et al., 2013). Yet, this observation is particularly important in the domain of spatial cognition of blind people. Indeed, in previous studies it has been observed that in contrast with sighted people, visually impaired people conserved spatial memory in an egocentric representation even at long-term (Cattaneo & Vecchi, 2011). It is commonly accepted that blind people usually encode spatial information in lower level procedural information and that they do not favor the construction of spatial survey knowledge (see Thinus-Blanc & Gaunet, 1997 for a review). In our study, delayed questions following map exploration tend to show the opposite: two weeks after exploration, lower level information related to landmark location is forgotten, whereas the high level information related to configurations is preserved.

It has to be noted though that pedestrian navigation and haptic exploration of a map are very different tasks. Both rely on sequential movements that help to encode the landmarks' location and the action necessary to spatially link each other. However, there are several differences between haptic exploration of an environment and exploration of a real environment. One difference lies in the cost related to individual processes that are performed. It is easy to move the hands back to a previous landmark on the map and thus obtain spatial relation between different landmarks. It is much less evident to walk back to a previous position in a real environment. This hypothesis is in line with the observation made by Lahav and Mioduser (2008) that the length of the path of exploration in a virtual environment was three times higher than in a real environment. This low-cost encoding process may favor the encoding and robustness of survey knowledge. Again, Lahav and Mioduser observed that the users who explored the virtual environment constructed a more robust spatial representation. Other differences, concerned the exploration strategies that are employed. Lahav and Mioduser observed that users employed a larger variety of exploration strategies when exploring the virtual environment. Thinus-Blanc and Gaunet (1997) report that using a larger variety of exploration strategies improved spatial knowledge. In addition, haptic exploration involves two hands. Bimanual exploration may provide immediate and useful information concerning relative location of different landmarks (Simonnet & Vieilledent, 2012). Finally, differences could simply be due to the different amount of information. Map representations are free of noise that exists in the real environment and may thus be easier to memorize (Ungar, 2000). Differences in the results of previous studies and our own observations concerning spatial cognition of visually impaired people may therefore be caused by differences between real world and map exploration.

IV.4.2.1.c Spatial Learning Depends on User Characteristics

As stated before (see subsection II.2.2.3), inter individual differences influence spatial cognition. Our results show correlations between performance and personal characteristics. Spatial scores for both maps were strongly correlated with self-evaluated expertise in reading tactile images. This means that subjects are aware of their own capacities. More interestingly, there are correlations between scores and navigation skills. For instance, effectiveness of the paper map was correlated with the sense of orientation; which means that users with better orientation skills performed better in the paper map tasks. In addition, landmark related scores on both maps were positively correlated with scores from the Santa Barbara Sense of Direction Scale and the sense of orientation. Subjects who evaluated themselves as having a good sense of orientation performed better in the recall of landmarks. This observation is consistent as many blind subjects received orientation and mobility training. It is not surprising that these subjects focus on landmarks to get oriented. Interestingly the learning of landmarks is improved if the interactive map is presented before the paper map. Most probably, getting in touch with an interactive map first might remove apprehension, increase map learning skills, and thus help read any kind of map at a later moment. Travel frequency, however, was negatively correlated with the scores related to survey knowledge on the paper map. Even if it is surprising at first glance, this makes sense. Indeed, the individuals who are frequent travelers are more used to looking for landmarks and routes than acquiring survey knowledge. It is a possibility that experienced travelers deeply focus on landmark identification and localization instead of acquiring survey knowledge.

IV.4.2.2 Users' Confidence in Map Exploration

In the first presentation of an interactive map, Parkes (1988) had raised the question if access to an interactive map could increase users' confidence in map reading. Until today, this question has not been answered. As mentioned before, we observed that the learning of landmarks is improved if the interactive map is presented before the paper map. In addition to this observation, we assessed users' confidence when using an interactive map as compared to using a tactile paper map. Following Parkes' proposition, our hypothesis was a higher confidence when using the interactive map. This hypothesis was neither confirmed at short-term nor at long-term. Yet, some interesting effects emerged. First there was a significant effect of time. Immediately after exploration, spatial scores and related confidence were completely coherent. Confidence in L responses was significantly higher than confidence in R and S responses. Hence there was a strong correlation between users' confidence and effectiveness (spatial scores) for both the paper and the interactive map. This means that users had a precise self-estimation of their performance immediately after map exploration. Two weeks after exploration, the spatial scores had been inverted with L scores being the least important. Users also lost confidence in their own responses but, surprisingly, confidence in L responses remained significantly higher than confidence in R responses. Users' perception of their own performance differed from real scores. One interpretation is that blind users are cognitively stuck to what they learnt to do, i.e. landmark detection. In reality, it appears that interactive map exploration improves long-term survey knowledge, which is more efficient to reach autonomous mobility (Siegel & White, 1975).

IV.4.3 New Technologies Impact Spatial Cognition

In this study, we observed that learning time for the paper map was correlated to self-reported expertise in using new technology. In other words, when subjects are confident in using new technologies, they need more time to explore the paper map with braille legend. Many of our blind participants reported that they were attracted by new technologies and tended to replace braille books and refreshable braille displays by audio books and audio output. This suggests that a proportion of blind people do not use braille regularly and less develop braille reading skills. Some of our participants even suggested that, in the long-run, audio output will completely replace braille. Today less than 10% of legally blind people in the United States and around 15% of blind people in France are braille readers (C2RP, 2005; National Federation of the Blind, 2009). Considering all these reasons, it is obvious that interactive maps are a more viable solution than paper maps with braille legend.

It is not surprising that the Santa Barbara Sense of Direction Scale and the self-reported sense of direction were correlated as both measure the same abilities. A higher expertise with traveling leads to a higher self-reported sense of direction. Interestingly the sense of direction was also correlated with the expertise in reading tactile images. As tactile images include tactile maps, it suggests that a better sense of direction can improve expertise in reading tactile maps and vice versa. This observation is potentially reflecting similar cognitive processes between haptic map exploration and whole body navigation. Furthermore, the expertise in using new technologies was positively correlated with the Santa Barbara Sense of Direction Scale. We suggest two possible interpretations. People with a well-developed sense of direction might have benefited from using personal navigation and orientation devices (e.g. Trekker[45] or Kapten[46]). We do not favor this explanation as it has been shown that electronic travel aids (such as GPS devices) are less effective for cognitive mapping (Ishikawaa et al., 2008; Münzer et al., 2006). On the other hand people who are experts in using new technologies are probably better connected to the internet. They might benefit from this by being more involved in social life. New technologies also provide them with the possibility to prepare trips. Thus these people might be less anxious in traveling, travel more, and by consequence develop a better sense of direction. Finally, we did not observe any correlations with the travel frequency. As our participants generally estimated themselves as frequent travelers, we suppose that a ceiling effect occurred that hindered us from observing any correlations.

[45] http://www.nanopac.com/GPS%20Trekker.htm [last accessed July 10th 2013]

[46] http://www.kapsys.com/fr/produits/kapten-mobility [last accessed July 10th 2013]

We also observed that ease of travel was negatively correlated with age and proportion of lifetime with blindness. Older participants and those with a longer duration of visual impairment lose confidence in navigation tasks. This means that they are less used to traveling and thus get excluded from social life. It is therefore important to propose solutions for this part of the population. Our study also revealed that the proportion of lifetime with blindness was positively correlated to the frequency of using new technology. This means that early blind people are used to, and probably benefit a lot from new technologies. This opens up a new perspective: using new technology can provide the elderly and early blind with a chance to improve space-related knowledge and skills. The use of interactive maps is promising for making geographic information accessible, for improving elderly users' mobility and orientation skills, and for reducing stress and fear related to travel.

IV.4.4 Limitations of this Study

In the present study, we compared two modes of interaction on maps that have absolutely identical contents. Yet, it would have obviously been possible to make different choices. The design of raised-line maps does not obey any standard. First, many production methods exist – the most common being swell-paper and vacuum forming (Edman, 1992). The production method may have an impact on tactile perception (Picard & Lebaz, 2012). We chose swell-paper. Second, the map content can vary from geographic to choropleth maps and have different scales. We chose to evaluate city maps. Third, the designer may use an infinite variety of tactile elements (symbols and textures) for representing geographic elements (Edman, 1992). In the present study, we designed maps that respect existing rules on the design of tactile maps (Edman, 1992; Picard, 2012; Tatham, 1991). We also made choices concerning the modalities and technology used in the interactive map. In the present study, we did not address if and how these choices impact spatial perception and learning.

As reported in section II.2 there is a large variation in mobility and orientation skills as well as tactile map reading skills among visually impaired people. It is important to mention that our subjects auto-evaluated themselves as being above average concerning mobility and orientation (mean SBSOD score = 5.15). Even if comparison of mobility and orientation scores concerning sighted and visually impaired people is limited, it is interesting to observe that the SBSOD has been used in studies with sighted people and has never been so high. Hegarty et al. (2002) reported the SBSOD scores of 221 participants with a mean score of 3.6. Ishikawaa et al. (2008) examined 23 participants and reported a mean score of 3.3. Our subjects backed up this observation when we interviewed them on travel frequency as well as travel confidence. A possible explanation is that visually impaired people who volunteer for a study concerning mobility and orientation are highly autonomous—they have to travel to the lab—and feel proud and confident regarding traveling. The characteristics of our users may have impacted the results concerning spatial cognition.

Limits may also lie in the questionnaires themselves. It has to be noted that the French translation of the SBSOD questionnaire is not standardized. However, there is no equivalent questionnaire that is standardized in French language. When working with non-English speaking participants, this problem is hard to avoid. Besides, Ishikawaa et al. (2008) potentially detected limits of the SBSOD questionnaire. They did not observe any significant relationship between participants' SBSOD score and wayfinding performance, except for one of the groups in their study. For the SUS questionnaire as for the SBSOD the French translation is not standardized. Further investigation is therefore necessary to assure that methods are correct and adapted.

Most importantly, the absence of a measurable effect of effectiveness is probably related to the small number of elements that were presented on the maps. A greater complexity might have led to different results. It would therefore be interesting to study usability of a more complex map.

IV.5 Conclusion

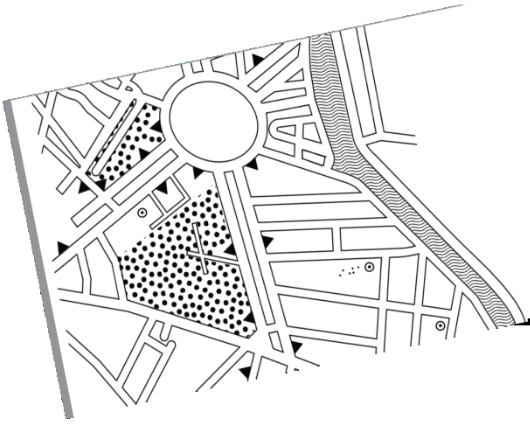
In this chapter we presented a study with 24 blind users. This study was composed of two parts: a short-term and a long-term study. The objective of the short-term study was to compare the usability of an interactive map and a paper map, both designed for visually impaired people. Our hypothesis was a higher usability for the interactive map and thus a better spatial learning (effectiveness), shorter learning time (efficiency) and higher user satisfaction. This hypothesis was partially confirmed: learning time was significantly shorter for the interactive map and more users preferred the interactive map over the paper map. Concerning spatial learning however, we did not observe any differences depending on the map type. Differences however were observed between the three types of spatial knowledge (landmark, route, survey). We observed that landmark knowledge shortly after exploration was significantly superior to route and survey knowledge. Furthermore, personal characteristics influenced the resulting spatial knowledge. For instance, we observed correlations between effectiveness and navigation skills. Interestingly the learning of landmarks was improved if the interactive map was presented before the paper map. We suggest that first exploring an interactive map might remove apprehension, increase map learning skills, and thus help read any kind of map at a later moment. The absence of a significant effect in effectiveness between the two maps is probably related to the small number of elements that were presented on the maps. We suggest that maps with a greater complexity might really benefit from interactivity.

In the long-term study we observed the effect of time on spatial information acquired from the two different map types. Our hypothesis was that long-term recall would be better after exploration with the interactive map. We did not observe any global influence of map type on long-term spatial recall. Significant differences, however, emerged according to the type of spatial knowledge (L, R, S). Contrary to the short term evaluation, survey scores were significantly more prevalent than landmark and route scores.

In addition, we studied users' confidence in their responses to spatial questions. We observed that users' confidence was closely correlated to their real performance just after map exploration. However two weeks after map exploration, confidence was highest in landmark questions, although participants obtained higher scores for survey questions.

Furthermore, we demonstrated the interest of interactive maps especially for people with low braille reading skills. Our study also revealed that the proportion of lifetime with blindness was positively correlated to the frequency of using new technology. This means that early blind people are used to, and probably benefit a lot from new technologies.

To sum up, these results provide an answer to Research Question 3 (How usable is an interactive map in comparison with a tactile paper map?). Interactivity appears to be promising for improving usability and accessibility of geographic maps for visually impaired people. We observed another significant advantage for interactive maps: the improved accessibility for people with low braille reading skills. More precisely, interactive maps seem to be a valid means for improving spatial cognition of visually impaired people. Specifically, they seem to favor survey knowledge, which is important for creating a cognitive map that facilitates flexible wayfinding.



Chapter V

Designing Non-Visual Interaction to Enhance Tactile Map Exploration

V Designing Non-Visual Interaction to Enhance Tactile Map Exploration

In the previous chapters we have opened up the design space of interactive maps for visually impaired people. We have also presented the design of interactive map prototypes based on iterative participatory design cycles. Furthermore, we concluded that interactive maps—based on raised-line map overlays and audio output—are more efficient and satisfying than classical raised-line maps with braille text. The interactive map in this study voluntarily included only basic interaction techniques to preserve functional equivalence with a raised-line paper map. Based on these previous results we decided to investigate Research Question 4 (How can non-visual interaction enhance tactile map exploration?). More precisely two sub-questions appeared to be important. First, as stated before there is still a lack of research on how visually impaired people read tactile maps (II.3.2.2.b). It seems important to better understand this behavior, in order to be able to design accessible and usable interaction techniques. Second, we aimed at exploring the use of advanced non-visual interaction to include further functionality in the maps. As explained before (II.4.3.2.a), there are few interactive map prototypes that make use of gestural interaction. We aimed at exploring the possibility to include basic gestural interaction into our interactive map prototype. Also, we studied how to design specific interaction techniques for route learning on an interactive map. These investigations are only of preliminary nature and open up avenues for future work in this field.

V.1 Observing Visually Impaired Users Haptic Exploration Strategies

In the background chapter of this thesis (II.3.2.2.b) we briefly discussed the impact of haptic exploration strategies for tactile image reading on the recognition performance. In this section we investigate this question in more detail. We then present an experimental platform for studying exploration strategies. We conclude with observations from preliminary studies.

V.1.1 Strategies for Exploring Tactile Images without Vision

There is an ongoing debate whether and how haptic exploration strategies influence the performance levels of image recognition and spatial cognition.

A first aspect concerns the number of fingers and hands used in the exploration process. Symmons and Richardson (2000) observed that sighted adults who were little familiar with the processing of tactile pictures preferentially used a single finger when asked to freely explore an image. Picture identification accuracy in sighted people improved if five fingers rather than one were used in the exploration process (Klatzky et al., 1993). Furthermore bimanual exploration of tactile images proved more efficient than exploration with only one hand (Wijntjes et al., 2008a). It can therefore be hypothesized that increasing the perceptual field improves raised-line picture identification.

Other studies investigated the existence of manual exploration strategies. Wijntjes et al. (2008b) observed three main strategies in tactile map exploration: 1) use of a single hand, 2) bimanual use with one hand moving while the other hand rests on the drawing, 3) simultaneous use of both hands. Sighted adults mainly used a "dynamic two-handed strategy". According to Wijntjes et al. (2008b), using two hands simultaneously facilitates the processing of tactile images, notably symmetry detection. In addition, using one hand as an anchor point while exploring with the other hand may facilitate the encoding of spatial information. In comparison, blind people seem to apply more efficient exploratory modes than sighted individuals. For instance, Heller (1989) observed that blind adults who used both index fingers outperformed sighted participants who used a single finger. Two possible explanations are suggested. First, the simultaneous use of two fingers could speed up information processing and reduce memory load. Second, one of the two fingers might serve as a spatial point of reference.

Recently, Vinter, Fernandes, Orlandi, and Morgan (2012) investigated the relation of visual status and exploration strategies on drawing performance after exploration of non-figurative 2D patterns. They encoded the following patterns: contour following, enclosure of the global shape, enclosure of local shapes, pinch procedure, surface sweeping, static contact and symmetrical movements. They observed that visually impaired children demonstrated a greater expertise during haptic exploration than sighted children. This was demonstrated through a more frequent use of bimanual exploration and a greater number of different procedures. Yet, some of the exploratory strategies employed by blind children, such as surface sweeping, led to poorly recognizable drawings. Furthermore, they revealed strong relationships between the exploratory procedures and their consequent performance in drawing. The resemblance between model and drawing was closer, when a greater number of strategies were employed.

There is a lack of literature investigating the cognitive processes related to raised-line map exploration. Many of the studies that we presented observed exploration of raised-line drawings of figurative objects. We believe that these findings are also applicable to the exploration of raised-line maps. Similar to tactile images, tactile maps need to be scanned sequentially which imposes high demands on working memory

(Jacobson, 1996). Ungar (2000) proposed that two-handed exploration facilitates learning through the relative simultaneity of input—in line with the observations of Wijntjes et al. (2008a). Jacobson (1996) argued that different haptic exploration strategies also influence the understanding of maps. Yet to confirm the validity of findings on haptic exploration for tactile maps, there is need for further studies.

To sum up, current research suggests that spatial cognition can be improved by employing systematic exploration strategies. It can also be concluded that increasing the perceptual field by using more than one finger, improves raised-line picture identification. It appears that visually impaired people possess an advantage over the sighted peers in employing systematic exploration patterns. However, the precise nature of tactile exploratory modes and the relations between exploratory strategy and performance level remain obscure and call for further investigation.

V.1.2 Kintouch: Observing Haptic Exploration Strategies

In this subsection we present an experimental platform for studying these exploration strategies in more detail. This section is based on the Master's Thesis of Céline Ménard under the supervision of Anke Brock (Ménard, 2011). Parts of it have been published in (Brock, Lebaz, et al., 2012).

V.1.2.1 Motivation

The above reported studies motivated us to further investigate haptic exploration strategies of visually impaired people. We identified three areas in which a better understanding of these exploration strategies would be useful. First, a better understanding of exploration strategies may help to identify and solve specific problems with the map itself. For instance the strategies might reveal ambiguous lines or symbols that are hard to identify by touch. Second, the knowledge could be used to improve guidelines on how to teach map exploration. For instance, if it were demonstrated that using one finger as a fixed reference point during the exploration enables better performance, then visually impaired students should be told to explore maps in this way. Third, this knowledge would enhance the design of adapted interaction techniques. Exploration strategies may highlight preferences for interacting with the map, for example, the role of different digits in the exploration process. This knowledge would give important insight into whether interaction techniques should make use of one or multiple fingers, and how to employ them.

The study of exploration strategies in psychology usually relies on video observation, which is time-consuming and cumbersome. A researcher has to watch the videos of the experiment and manually code the different strategies when they are used.

In order to ensure against errors, often two or more researchers code the same videos and then results are compared. In order to make the process more efficient, our goal was to design a system for automatic tracking and identification of the fingers used when exploring the tactile image.

V.1.2.2 Concept

In a first step we needed to identify a technology for tracking fingers. Many previous projects have focused on finger tracking. The majority were based on automatic recognition in video, tracking either bare hands (Kane, Frey, et al., 2013; Krueger & Gilden, 1997) or markers of different kinds. For instance, Schneider and Strothotte (1999) and Seisenbacher et al. (2005) used color markers for tracking fingers during the exploration of tactile maps. More recently depth cameras have been used (Harrison & Wilson, 2011; Wilson, 2010a). Other projects used optical multi-touch surfaces for finger tracking and identification (Dang, Straub, & André, 2009). In contrast to electric touch tables, optical touch tables allow to recognize not only the different fingers position but also their orientation and sometimes even the form of the hand. However, as reported in section III.2.3.3 it is not possible to use an electric multi-touch table with a raised-line overlay. A different technology has been employed in a proof-of-concept prototype (Munkres, Gardner, Mundra, Mccraw, & Chang, 2009). In addition to a classical finger tracking in a video image based on color markers, Munkres et al. developed a new concept. It was based on tracking finger position with a digital device attached to the finger. However, this device was cumbersome and it was only possible to track one finger with this apparatus.

In response to the analysis of literature we came up with the idea to make use of the previously developed interactive map prototype for the tracking of fingers. However, the 3M projected capacitive multi-touch screen M2256PW has two important limitations. First, it can only track the position of fingers that actually touch the surface. Yet, the goal for this prototype was to track all finger movement, including fingers above the surface. Second, the multi-touch table cannot identify which hand (left or right) and which finger (i.e. the thumb, index, etc.) caused the touch. For two successive touches, it is not even possible to determine if they were made by the same or two different fingers. In contrast with optical tables as mentioned above, the capacitive screen only indicates a touch position and not the form and orientation of the touching finger. Third, it is not possible to determine whether the touch event is provoked by a finger or another body part, such as the palm of the hand. Yet, these unexpected touch events would have to be considered as false positives as we only wanted to track fingers and not the palms of the hand.

Another idea was to make use of the Kinect camera as proposed by Wilson (Wilson, 2010b). First of all, Wilson demonstrated that is possible to use the Kinect camera to detect finger positions and even for gestural interaction. Second, fingers are detected even if the surface is not flat (i.e. the relief of the tactile map does not disrupt detection). Third, it is possible to obtain information about digits that are not in touch with the surface. On the negative side, the precision of the Kinect as a depth sensor is inferior to the precision of a touch surface (Wilson, 2010a).

To overcome the limitations of both devices, we decided to merge finger detections from the Kinect with touch events from the multi-touch screen. The aim was to get precise information regarding hands and fingers involved during the exploration of a tactile map.

V.1.2.3 Kintouch Prototype

In this subsection we present the hardware and software that were developed for our prototype.

V.1.2.3.a Hardware

Kinect

multi-touch screen and raised-line overlay

Figure V.1 Kintouch hardware setup: multi-touch screen with raised-line overlay and Kinect camera.

Our prototype (Figure V.1) consisted of a multi-touch screen in horizontal position, a tactile map, a Kinect camera fixed above the touchscreen at 70 cm height and turned in the direction of the touch screen, and a computer connected to touch screen and Kinect.

The multi-touch screen was the 3M projected capacitive multi-touch screen M2256PW as in the previously developed map prototype (III.2.5.4.b).

The Kinect camera combines a depth sensor that allows visual reconstruction of 3D objects and a RGB (red, green, blue) color camera. It has originally been developed as a controller for video games. Due to its low price and practicality it has recently been used in many research projects. Its use for development purpose is now officially supported by Microsoft. By the time we started the project however, the official drivers were not yet available.

V.1.2.3.b Software

The software for this prototype consisted of three applications: one for detecting finger positions on the touch screen as in the experimental interactive map prototype (III.2.5.4.b), a second for finger tracking in the Kinect image and a third for merging the results. The first application was based on the previous interactive map prototype. As in the modular software architecture of the interactive map prototype (III.2.5.2.a), data was sent via the Ivy middleware (Buisson et al., 2002). Each touch event contained a timestamp and x and y coordinates. The second application was based on the Kinect. Its output contained the name of the finger (thumb, etc.) and corresponding hand (right or left), x and y coordinates of the finger and a timestamp. Kinect and multi-touch data was then written to a log file. A third application called "fusion" (used for offline processing) read this data and merged it. It then created another output file that contained the name of the fingers and corresponding hand, x and y coordinates of the fingers, whether the fingers were in touch, and a timestamp.

As the multi-touch application has been described in details beforehand, in this subsection we will only present the Kinect finger tracking and the fusion as well as the user interface of the application.

Finger Tracking

Image recognition is challenging in several aspects such as the lighting or noise in the image and it is not easy to achieve a stable identification of objects. To reduce the amount of information to process, finger tracking was only done on an excerpt of the image (see Figure V.2). In order to further facilitate the image processing, we proposed the following four hypotheses. First, while exploring a map, users' hands are always turned with the palms downwards. Second, the surface is flat (except for the relief on the map). Third, only hands and arms and no other body parts are moving in the camera image. Fourth, the map stays in position.

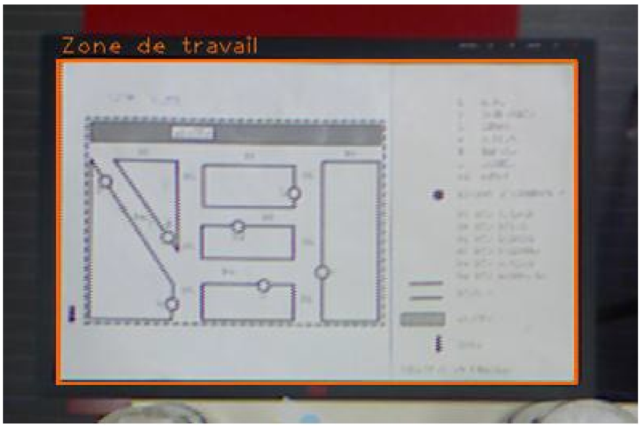


Figure V.2: Limiting the working zone in which image recognition is done (French: "zone de travail") to the actual map. Reprinted from (Ménard, 2011).

As the Kinect possesses two cameras (depth and RGB), it was easy to implement and compare two different algorithms within the same setup. Both algorithms used OpenCV[47] functions and OpenNI middleware[48].

Depth Image

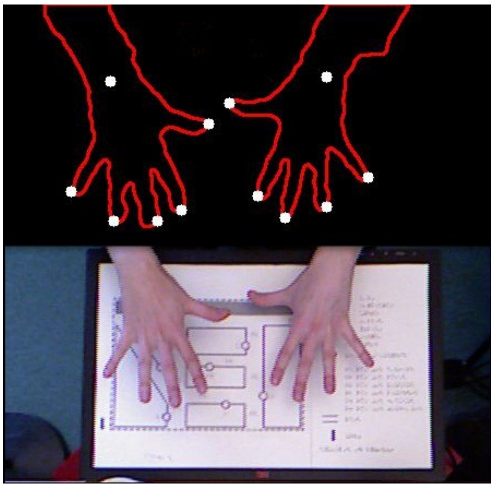
A first algorithm used the depth image (Figure V.3 a). The calibration phase consisted of two steps. First, a depth mask was created to segregate objects (i.e. hands and digits) from the background (i.e. the tactile map). Second, the user held their hand horizontally with the fingers spread. Maximum angles between fingers were measured by the application. They were then used as additional constraints on finger identification.

After calibration OpenCV functions for noise reduction were applied. The image was converted into a binary image. Contours were detected as lists of connected points. In the next step it was then necessary to identify contours that corresponded to hands, as false positives from noise in the image could occur. For this a minimum size threshold for the contour was applied. Then, each contour was reduced to the minimum number of points needed to form the outline of the hand because sometimes it was composed of redundant points. The resulting segments corresponded to outlines of the fingers and vertexes of the contour represented fingertips. By using the depth information from the image it was possible to calculate the fingers that actually touched the surface.

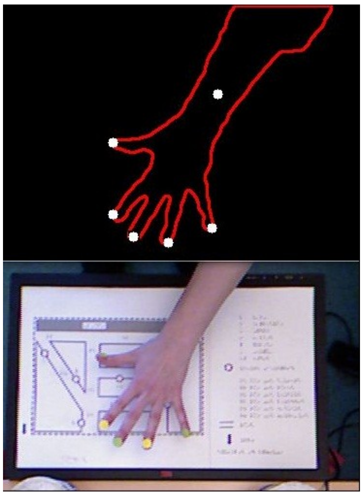
[47] http://opencv.willowgarage.com [last accessed July 7th 2013]

[48] http://www.openni.org [last accessed July 7th 2013

To identify finger types, the recognized fingers were ordered based on angles between them. The biggest angle existed between thumb and index. This identification could be done easiest in the calibration phase when all fingers were spread and visible in the image. Finger positions in the previous image were taken into account to stabilize detection. Thus it was possible to identify fingers in the calibration image and continuously track them. Given the hypothesis that the hands were always turned with the palm downwards it was easy to identify the right and left hand once the thumb was identified. As a final result of this algorithm, each detected finger was part of a hand (right or left) and had a name (thumb, index, etc.) and information whether it touched the surface or not. A special challenge for this approach was when users closed the hand partially so that some fingers disappeared from sight. However, as long as some of the fingers were visible, the algorithm kept track of fingers quite successfully.



(a)



(b)

Figure V.3: Tracking of the user's fingers. (a) Result based on depth image of the Kinect camera (above) and real hand position (below). (b) Result based on RGB image of the Kinect camera (above) and real hand position with color markers attached to finger tips (below). Reprinted from (Brock, Lebaz, et al., 2012).

A second algorithm was developed as an alternative. It identified fingers in the RGB image with the help of color markers attached to the fingertips (Figure V.3 b). Two different colors applied to alternating fingers were sufficient in order to track the finger identifiers. The image was transformed into HSV (hue, saturation, value) colors. Using the saturation instead of the RGB colors eliminated problems caused by lighting. During calibration and in addition to the process described above, the experimenter clicked on the two colors in the image which enabled the algorithm to identify fingers by color tracking. Angles and last finger positions were used as described in the depth image algorithm. This algorithm required additional preparation before the experiment as adjusting color markers to the fingers took about 5 minutes. However, due to the additional color information this algorithm proved more stable for finger detection.

Fusion Algorithm

The aim of the fusion was to combine and correlate touch events obtained from the multi-touch surface with the finger detections from the tracking algorithm. We had the choice to implement the fusion online, i.e. at real time while running the applications, or offline, i.e. after running the applications. As an advantage of the online fusion, it would have been possible to use fusion results at runtime for correcting tracking of the Kinect or the multi-touch table. On the downside, we suspected the fusion to be time consuming and thus we feared that online fusion would slow down the application. The offline fusion also appeared easier to implement. Furthermore, the offline fusion provided the possibility to keep the log files for later analysis. The disadvantage of the offline fusion was the need for memory for saving the log files. Based on this analysis we decided to implement an offline fusion. However, it would be possible to change the fusion mode.

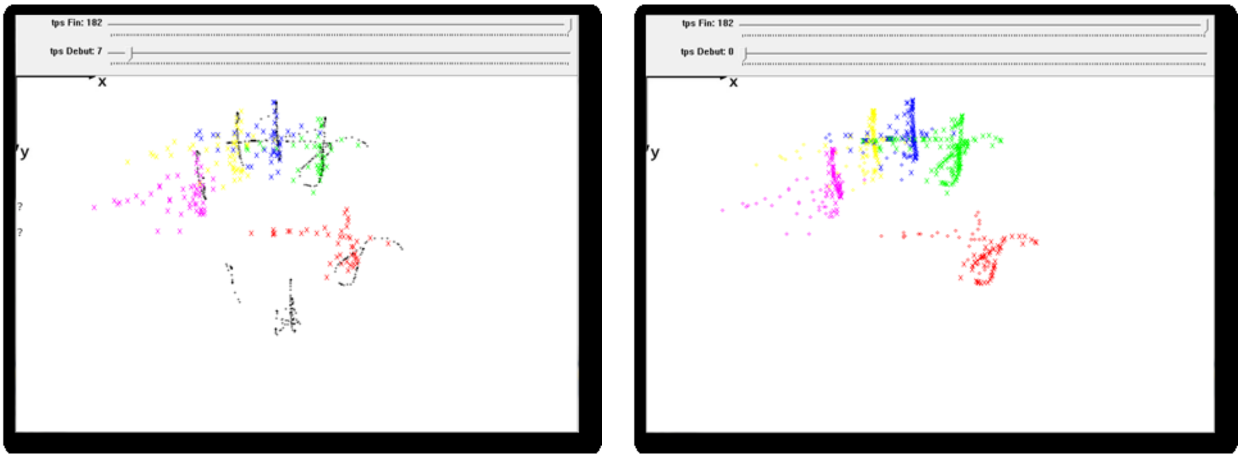


Figure V.4: Finger tracks before (a) and after (b) fusion. (a) Black : tracks from the Multi-touch table; colored tracks are from the KINECT (red thumb, green index, blue middle finger, yellow ring finger, pink pinky). (b) Colored tracks after fusion (red thumb, green index, blue middle finger, yellow ring finger, pink pinky); tracks above the surface are marked by an "O"; tracks in contact with the surface by an "X". Reprinted from (Ménard, 2011).

Kinect and multi-touch table did not possess the same coordinate system. The Kinect had a resolution of 640x480 pixel, whereas the multi-touch table had a resolution of 1680x1050). After limiting the image recognition zone (see Figure V.2), the touch surface corresponded to approximately 330x221 pixels in the camera image. This resulted in a precision of approximately 1.4 mm/pixel in the camera image, which is sufficient when compared to the size of the fingertip. The precision of touch events was 0.28 mm. The formulas for the coordinate transformation are described in (Ménard, 2011). Comparing the resulting coordinates with the actual finger position revealed a calculation error of about 20 pixels. Although this precision seemed quite low, we validated during the preliminary tests that it was sufficient to match positions of the same finger from the multi-touch screen and the Kinect.

Temporal accuracy is important for fusion. Touch events were produced at 100 Hz; finger detections and fusion output at 10 Hz. Both sources produced a lot of data (the multi-touch data produced several samples per millisecond) and not necessarily at the same timestamp. Therefore we limited the fusion to samples of 10ms. In pretests it proved to be sufficient.

The fusion application read log files that contained both multi-touch and Kinect data. One of the two variants of the finger tracking could be selected. Multi-touch events contained a contact identifier, x and y coordinates and a timestamp in milliseconds. Finger detections from the KINECT contained a name for the finger, the type of hand (right or left), x and y coordinates, if the finger was touching the surface and the timestamp in milliseconds. For each touch event, the algorithm searched for the finger detection with the closest position. Finger detections that had not been matched to touch events were considered as fingers above the surface. Touch events that did not correspond to finger detections were considered as false positives and removed (Figure V.4). The fusion application provided visualization with the possibility to adapt the time frame.

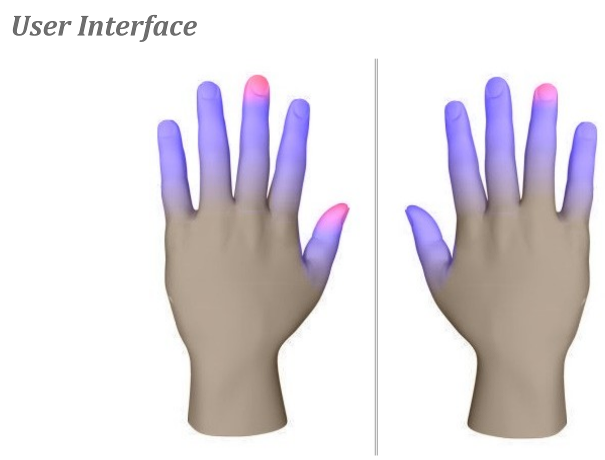


Figure V.5: Visualization of tracked fingers. Identified fingers are depicted in violet and fingers touching the surface in pink. Reprinted from (Ménard, 2011).

The interface for the application was developed with the GTK library[49]. Its purpose was to provide the researcher with an application for calibrating, choosing between the

[49] http://www.gtk.org/ [last accessed July 8th 2013

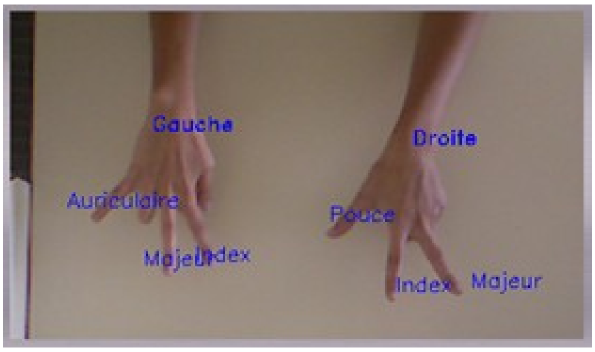
two algorithms and observing the tracking algorithm during execution. Visualization showed the tracked fingers and which fingers touched the surface (Figure V.5). More details on the user interface are described in (Ménard, 2011).

V.1.2.4 Case Studies

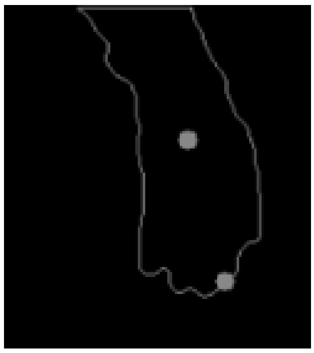
We did preliminary tests with both algorithms and offline fusion. Two aspects were important to us: (1) It has been proven that cameras can be used for finger tracking in touch sensors (Harrison & Wilson, 2011; Wilson, 2010a). However, these studies have been done in a different context. We wanted to check that those algorithms were adapted to finger tracking during exploration of a tactile image. (2) We wanted to get concrete fusion results (i.e. success rate of the fusion, usage of different fingers, etc.) in order to decide if this approach could be used for analyzing haptic exploration strategies.

The test subjects were three blindfolded (2 female, 1 male) and three legally blind (1 female, 2 male) participants. Participants possessed different levels of expertise in tactile map exploration based on the assumption that this factor impacts exploration strategies. Two of the blind participants had significant expertise in map reading, whereas the third blind and the blindfolded participants had little expertise. We reused the simple tactile map from the experimental study which contained six streets, six buildings, six points of interest and a river (see IV.2.1.1). For each test, participants were asked to explore the map in the way they normally do, or if they did not have previous experience in the way that spontaneously felt natural.

V.1.2.4.a Using Depth Camera



(a)



(b)

Figure V.6: Tracking of the fingers with the Kintouch prototype. (a) Detection was working even when some fingers are occluded (names of fingers are indicated in French). (b) When fingers were close to each other, the depth image algorithm perceived the hand as one blob and separation of fingers was not possible. Reprinted from (Ménard, 2011).

The depth camera based algorithm proved efficient with most of the subjects: fingers were successfully detected and identified. Obviously, occluded fingers were not detected. Yet, the occlusion of some fingers did not hinder the correct identification of the remaining fingers (Figure V.6 a). Reappearing fingers were identified within one video frame. However the algorithm failed with one blind subject with good expertise in map reading. As a part of his exploration strategy, he frequently closed his fingers so they were no longer sufficiently separated (Figure V.6 b). Hence we concluded that the algorithm is globally working, but does not support every user's exploration behavior. Consequently it would be problematic to use this algorithm for studying haptic exploration strategies.

V.1.2.4.b Using RGB Camera

As described before, for this algorithm color markers were placed on the finger tips before map exploration. We observed that detection was stable for all users and that their behavior did not interfere with the algorithm. In contrast with the depth image, this algorithm proved efficient when the fingers were spread out as well as when they were closed. It did not depend on the number of fingers involved. Occlusion of certain fingers did not hinder the correct identification of remaining fingers. Reappearing fingers were identified within one video frame. However, wearing a watch led to reflections that were sometimes detected as a marker. The most important point was the need to fix color markers on the fingertips. We originally wanted to avoid this to make interaction as easy and natural as possible. However we decided that the gain in stability of the detection algorithm compensated for the loss in flexibility.

V.1.2.4.c Fusion

Figure V.7: A blindfolded participant testing the Kintouch prototype. Reprinted from (Ménard, 2011).

Based on these preliminary results, we selected the RGB image based algorithm for continued evaluation of the complete fusion process. We evaluated the fusion algorithm with data from the map exploration of one male blindfolded with no prior tactile map reading experience (see Figure V.7).

The user explored the map for approximately 2 minutes. The data was stored in a log file. The fusion application then ran the log file through the fusion algorithm. After fusion, 98% of the detected fingers were identified, i.e. name of finger and hand were attributed. For each finger it was possible to determine whether it touched the surface or not. 95% of the detections were identified as touches which means that most of the time the subject was using all of his fingers for map exploration. Both hands were used almost equally. The thumbs were least used with only 3.4% of touches. His left ring finger was the finger having the most contact with the map (19%). This was surprising, as we did not expect it to be the finger typically used for map exploration. Yet, of course this depends on personal exploration behavior and the user had no prior tactile map reading experience. Therefore his haptic exploration strategies may not have been the best adapted strategies.

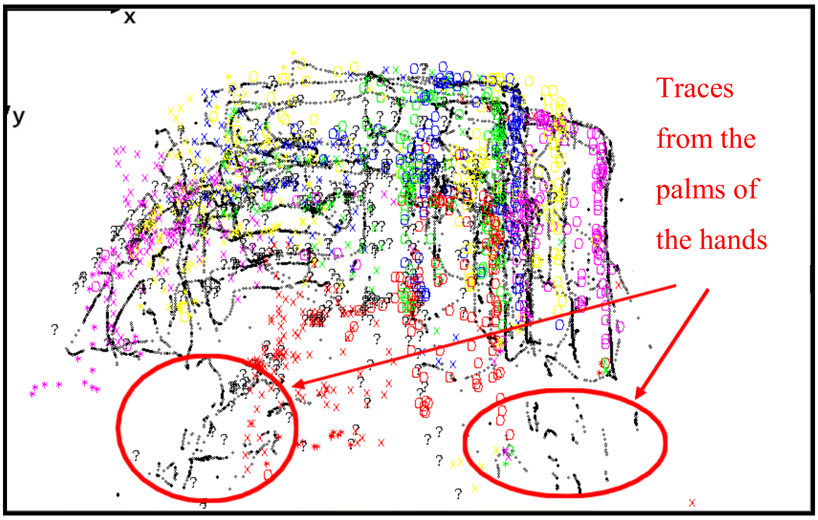


Figure V.8: Visualization of the data in the log file before fusion. Traces marked in red resulted from the palms of the hand that rested on the surface during map exploration. Reprinted from (Ménard, 2011).

As can be seen in Figure V.8, the palms of the hand had rested on the multi-touch screen during map exploration. The fusion successfully removed false positives from the palms. The result can be seen in Figure V.9.

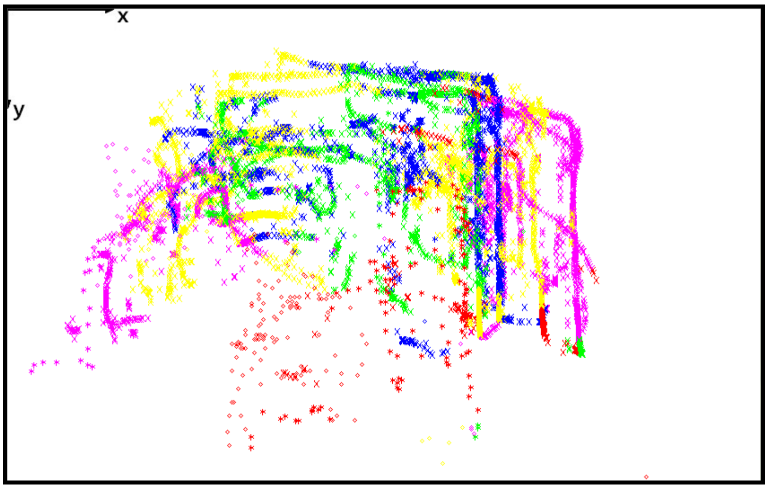


Figure V.9: Visualization of the data in the log file after fusion. Traces from the palms of the hand have been removed. Reprinted from (Ménard, 2011).

The visualization tool in the fusion application provided the possibility to select the time frame for displaying the finger traces. We suggest that it would additionally be interesting to select one or several fingers in order to study their movement separately. Furthermore, we propose to match the finger traces to the map content in order to identify the relation between exploration strategies and map features. We exemplarily visualized the traces of the right index finger with a simple visualization in Windows Excel (Figure V.10). The temporal distribution is represented through different colors. The finger first touched the red positions, then the green positions and then the blue ones. From the red traces we can for instance conclude that the user followed the outline of the buildings. Also his finger rested some time at the upper point of interest (blue traces). Furthermore he worked his way from the bottom of the image to the top. Of course, more detailed analysis would be necessary to obtain precise results and to study in a next step how the employed strategies impact the resulting cognition.

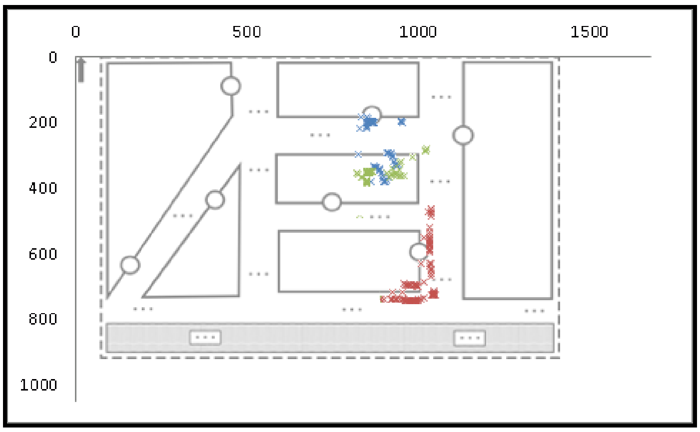


Figure V.10: Spatial and temporal visualization (see colored traces) of movements made by the right index during map exploration matched to the map content. Colors indicate the successive positions of the index finger (1 red, 2 green, and 3 blue). Reprinted from (Brock, Lebaz, et al., 2012).

V.1.3 Conclusion and Perspectives

In this section we presented an experimental platform for the study of haptic exploration strategies for reading tactile images. However, this prototype possessed some limitations that we discuss in the following subsection. We also present possible perspectives for using the prototype for studying haptic exploration strategies.

V.1.3.1 Limitations and Possible Improvements

As presented above, results from preliminary evaluations of the Kintouch prototype are promising. Nevertheless, the prototype still has some flaws that need to be improved.

First, we observed problems related to the Kinect. We originally chose to use the Kinect because the depth image sounded promising for easily distinguishing fingers and hands from the background. Yet as reported above, it was not possible to identify fingers if the user explored the map with closed hands. Therefore the depth camera cannot be used for studying haptic exploration strategies. However, it makes less sense to choose the Kinect for the RGB camera, as there are color cameras available with a higher resolution. Therefore it might be preferable to opt for a color camera with a higher resolution. This would then also increase precision of the fusion results, which in the current application is quite low.

Second, the solution of using colored markers on the finger tips is not optimal. Having a marker glued to the finger nail during exploration of a map, might hinder the natural exploration movements. As the markers were small we suppose that they do not impact the exploration behavior. Yet, it would be desirable to develop an algorithm which can detect bare fingers without markers. However, technically this is challenging.

Third, we identified the need for a more powerful visualization tool. As we have argued before, we would need not only a tool that allows selecting the time frame to be displayed, but also to select one or multiple fingers. Furthermore it should be possible to match the fingers to the actual map content.

Once the prototype is improved, we would also need a tool that can actually analyze the resulting traces from the fusion. So far we only see where the fingers passed but we still have to analyze the image manually to understand what it means. An improved functionality would be that the computer automatically identifies exploration patterns. But first, it would be necessary to decide which patterns should be used. For instance, patterns could be based on the proposition of Wijntjes et al. (2008b) to differentiate use of a single hand, bimanual use with one hand moving while the other hand rests on the drawing, and simultaneous use of both hands. A different possibility would be to encode patterns such as contour following, enclosure of shapes, pinching, surface sweeping, static contact and symmetrical movements as proposed by Vinter et al. (2012). The choice of the procedures to be encoded would actually depend on the hypothesis and protocol. It is only after implementing this step, that the prototype would be really useful for studying haptic exploration strategies.

As an alternative, this prototype might also serve as the basis for developing a tool for recognizing gestural interaction above the surface.

V.1.3.2 Perspective: Experimental Protocol

After implementation of the improvements, we may suggest how experimentation could be done. Let's say the hypothesis of our study is that using more than one finger for raised-line map exploration is advantageous for spatial cognition. We would then want to study whether it makes a difference on the resulting cognitive map if the user explores the raised-line picture with one finger, several fingers of the same hand or both hands; and then how these fingers are employed. The prototype should then recognize at least the following exploration patterns: 1) exploration with one finger; 2) exploration with several fingers of the same hand, 3) exploration with several fingers of both hands. For each finger the system should identify its type (thumb, index, etc.) and whether it belongs to the right or left hand. It may be useful to automatically identify further information such as if the finger is staying in place or moving so that it is possible to identify whether a finger serves as a reference point or if it is involved in the kinesthetic exploration.

Subjects in the study should be visually impaired because it has been proved that haptic exploration strategies differ between visually impaired and sighted participants. If we want to understand visually impaired people's tactile map reading strategies, we therefore need to test with them.

Based on our hypothesis, we would want to measure at least one dependent variable which is the spatial knowledge resulting from map exploration. As presented before, several possibilities exist for evaluating spatial knowledge with visually impaired people (II.2.2.5). We would also suggest measuring the time that the subject takes for map learning, because it may correlate with the resulting cognitive map.

There would be several consequences from the possible outcomes of such a study. First, the study could have an impact on the teaching of map reading strategies. If the study revealed that high performers use specific exploration patterns, these patterns should be taught to visually impaired students. Likewise, if certain patterns lead to poor performance it should be made sure that visually impaired people do not employ these patterns. Second, identifying successful haptic exploration strategies could influence the development of accessible interaction techniques. Let's say that bimanual exploration leads to better cognitive mapping, then non-visual interaction for maps should support bimanual exploration. If using a fixed reference point improves distance knowledge, than interaction techniques for learning distances should be based on this principle. Indeed, the development of accessible interaction today is not grounded on insights from cognitive science. In our opinion it is important to take into account this knowledge when developing interaction techniques in order to develop systems that are even more accessible and usable.

V.2 Enhancing Maps through Non-visual Interaction

As previously discussed (see II.3.3.2), maps that are traditionally used for visually impaired people—raised-line maps—come with limitations. For instance, the use of braille is challenging. Other limitations of raised-line maps concern the fact that only a limited amount of information can be represented in order to avoid cognitively overloading the map reader (Tatham, 1991). Furthermore, specific information such as distances is difficult to present on raised-line maps. Lastly, the map content is static and cannot be adapted dynamically.

In addition, we have presented the design space of interactive maps for visually impaired people (see II.4). Many non-visual interaction techniques can be used to provide information. For instance, we have shown that the use of speech output can help overcome problems related to braille. Yet some of the above mentioned limitations remain to be solved. For example, interactive maps often are limited to announcing the name of landmarks and streets but do not provide further information, such as opening hours. Also information—such as distances—often remains inaccessible.

In this section we present a proposition for including supplementary functionality into the interactive map prototype by integrating advanced non-visual interaction. In a first step, we investigated use of basic gestural interaction. In a second step, we concretely investigated how to design interaction techniques for route learning.

V.2.1 Providing Functionality through basic Gestural Interaction

We believe that for commercializing interactive maps, it would be interesting to provide more functionality and information as is currently the case in most prototypes (i.e., more than just names of streets and points of interest). It has been demonstrated that gestural interaction can be designed for visually impaired users (see II.4.3.2.a). Yet so far, few interactive map projects for visually impaired people made use of more complex gestures than tapping. The aim of this part of the project was to study how basic gestural interaction could be used to enrich the interactive map prototype with extended functionality. This work was developed during the internship of Alexis Paoleschi under the supervision of Anke Brock (Paoleschi, 2012).

V.2.1.1 Analyzing Possible Use of Gestural Interaction

Gestural interaction would provide the possibility to enrich interactive maps. First it would make important information accessible, such as distances, directions, or itineraries. Distance information has previously been implemented in the Talking TMAP prototype (Miele et al., 2006). As this prototype was based on a mono-touch display, the calculation of distances was done with a combination of taps with a single finger. We propose that using more than one finger could facilitate distance calculation.

Second, it would be possible to present more information. However it would still be cognitively demanding if too much information was presented at once. To this regard, participants in our studies (see chapter III) have stated that they would like to choose the amount and type of information that is presented on the map. This possibility has been provided in prior map projects. For instance, Strothotte et al. (1996) proposed three levels of information: essential, desirable and ideal. Essential information contained for instance street names and distances, desirable information contained information on buildings and public transportation, ideal information contained roadwork. De Felice et al. (2007) presented a map of a region in Italy with different layers of information. A first layer displayed shapes of provinces and borders with other regions and the sea, a second layer rivers and lakes, and a third layer major towns. In the Talking TMAP project (Miele et al., 2006), different levels of information could be accessed through repeated tapping. This information included names of streets, address ranges, length of the street and spelling. Similarly, in the BATS project (Parente & Bishop, 2003) users could access names, population, and area of counties by repeatedly pressing a button. Weir et al. (2012) and Lazar et al. (2013) distinguished different levels of information through auditory feedback. In a first level, information was represented through a tonal feedback, whereas in a more detailed level spoken information was given. User could access different levels through pressing a key. Levesque et al. (2012) compared three conditions for exploration of a tactile drawing by visually impaired people: 1) a drawing with static content, 2) a drawing where users could manually adapt the level of detail, 3) a drawing where the level of detail was automatically determined from speed of hand movements.

Although there was no significant difference in reading speed or error rate, users clearly preferred the mode in which they could manually toggle the amount of detail.

Taken together, this demonstrates the interest of providing access to more detailed information and of letting the user choose the level of detailed that is displayed. It also seems desirable to provide access to supplementary information, such as distances.

V.2.1.2 Designing Non-Visual Gestural Interaction

As discussed above (V.1), before designing gestural interaction for interactive maps, we should ideally have more insight on the relationship between haptic exploration strategies and spatial cognition. However, this information is not yet available. Yet, the participatory design process also ensures that developed interaction techniques are usable and accessible through including users in the process.

Therefore we proceeded as in the previous projects and employed brainstorming sessions. Due to the time constraints of the internship during which the work was done, it was not possible to work as closely with visually impaired people as during the previous development on the interactive map. The presence of a blind researcher during the sessions assured at least taking into account needs concerning accessibility. Additionally, we based our brainstorming on user feedback obtained in previous sessions. For instance, during the Wizard of Oz experimentation (see III.2.4.2), users had expressed their interest for accessing information on public transports. Also several users had stated that they would appreciate having several levels of information (for example names, information on opening hours) and the possibility to switch between them. Distance also seemed to be important.

The brainstorming session took place between one blind expert and four sighted researchers. We discussed how to make use of gestural interaction within the same interactive map concept, i.e., touchscreen with raised-line overlay. Among the ideas that we retained was the possibility to select different levels of information. For instance with the same interactive map, it could be possible to switch between the audio output for basic points of interest, opening hours, or public transportation. We proposed the combined use of buttons and basic gestural interaction to access this different information. Additionally, we came up with the idea of integrating a dynamic braille display as an alternative output interaction. Also, we decided to explore how distance information could be provided.

V.2.1.3 Prototyping Gestural Interaction for Map Exploration

We developed a prototype based on the experimental platform presented in section III.2.5.4.b and used in the evaluation presented in chapter IV. However, for this prototype we replaced the Ivy-based modular software architecture by the MT4J Gestural API as presented in the subsequent subsection. Thus, we added basic gestural interaction. We also inserted additional buttons in the map drawing. The S.I. VOX / Vocalyze software (III.2.5.3.b) was used for speech output. As a complement we connected a braille display as a proof-of-concept. Figure V.11 shows a photograph of a user exploring the prototype.

We decided to provide the possibility to access different types of information by combined use of buttons and gestural interaction techniques. The buttons served to change the mode, i.e. the system state (Foley et al., 1996). Each system state then provided access to different interaction techniques. By doing so, we wanted to reduce the risk of accidentally executing gestural interaction.

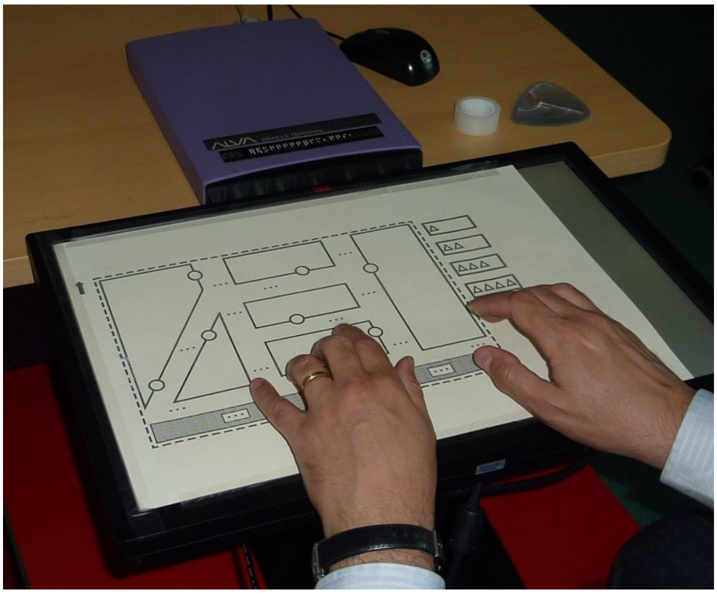


Figure V.11: Exploration of the gestural prototype. The map drawing contains four buttons for accessing different information modes (right side of the drawing). The image also shows the braille display placed behind the screen. Reprinted from (Paoleschi, 2012).

V.2.1.3.a Gestural API

The modular software architecture that we used in the interactive map prototypes (III.2.5.2) was advantageous as long as we changed the experimental setup (for instance the touchscreen). It was then easy to replace software modules in order to adapt to the new setting. However, it also presented challenges regarding robustness. More importantly however, it was difficult to implement gestural interaction. Different multi-touch APIs (Application Programming Interfaces) provide this possibility more easily.

Therefore, a second software architecture was based on using a Gestural API. Following a preliminary analysis of multi-touch APIs (see subsection III.2.5.2.b), we have chosen the API Multi-touch for Java (MT4J).

MT4J is a toolkit for development of multi-touch applications (Laufs, Ruff, & Weisbecker, 2010; Laufs, Ruff, & Zibuschka, 2010). It is an open-source and cross-platform framework. MT4J is released under the GPL license and can be freely used. Its architecture consists of four different layers: Input Hardware Layer, Input Hardware Abstraction Layer, Input Processing Layer and Presentation Layer. These layers are connected through events, sent from one layer to the next. Input events are produced in the Hardware Layer by the underlying hardware. The Hardware Abstraction Layer converts raw input data into unified input events. By doing so, MT4J supports different hardware such as multi-touch screens, keyboards or mice. Unified input events are produced and passed to the input processors on the Input Processing Layer. This layer actually includes two different processing stages. First, input specific functionality (e.g., displaying a cursor) is produced by the global input processor. Second, component input processors translate the input events to higher level gesture events. One gesture processor exists for each specific gesture (e.g., rotate, lasso). The user interface components on the Presentation Layer then receive the gesture events and react by performing the desired action.

V.2.1.3.b Map Drawing

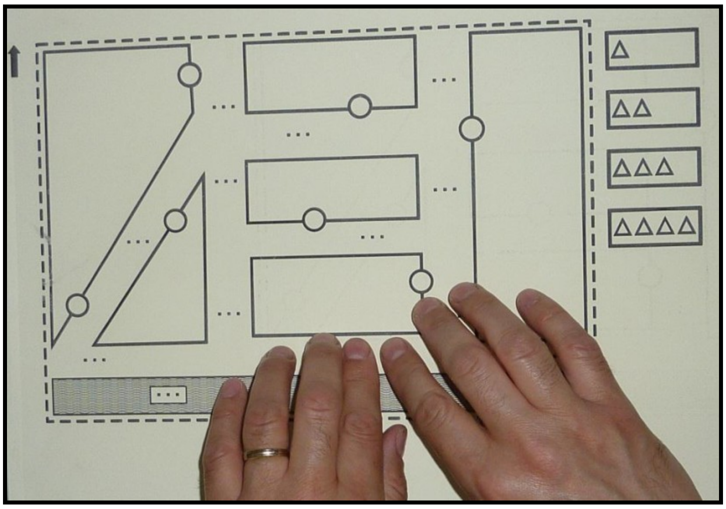


Figure V.12: Detailed view of the raised-line overlay with the four buttons on the right side. Reprinted from (Paoleschi, 2012).

The map drawing was largely based on the map drawing from the experimental study (IV.2.1.1). However, in order to provide the possibility to access different modes and levels of information, we decided to add "buttons" on the map. These buttons were actually rectangles printed in relief. The buttons were ordered from level one to four by an increasing number of triangles. Figure V.12 shows the map including four buttons for switching between different levels of information.

V.2.1.3.c Gestural Interaction

One objective of this project was to test whether gestural interaction techniques could be useful for exploration of interactive maps by visually impaired people. We decided to make use of the basic interaction provided by the MT4J API. Among the basic interaction techniques, MT4J provided a lasso gesture. A lasso gesture is a circle path around a map element without lifting your finger (see Figure V.13 b). This gesture has been successfully used in applications for sighted people (Sang et al., 2013). Additionally, we implemented a tap and hold gesture. The user had to tap and hold on a map element. A beep sound confirmed the activation while continuing to hold the finger. The user could then tap on a second map element and a second beep would confirm the activation. The distance between both elements was then announced.

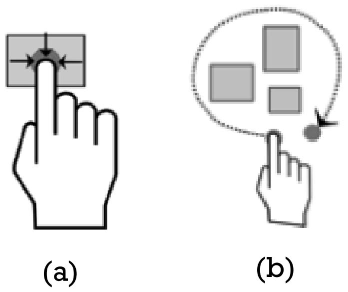


Figure V.13: Different gestures used in the system, (a) Tap gesture, (b) Lasso gesture. Reprinted from (Laufs, Ruff, & Weisbecker, 2010) with permission

V.2.1.3.d Software Architecture Based on Gesture API

The architecture of this prototype varied from the previous in that it was centered in one main application using MT4J and not distributed in several modules.

MT4J possesses the possibility to design graphically rich user interfaces. This is, of course, of little importance for our application that targets visually impaired people. Nonetheless the experimenter needs a visual view of the map for preparing the experimentation. In MT4J the graphical user interface is created as a scene graph. It is based on a hierarchic structure of components. Creating such a component tree is done by attaching components ("children") to other components ("parents"). A component can have one parent component at most while the number of child components is not limited. For initializing the scene graph it is necessary to choose a name, a background image and load default parameters, for instance resolution and full screen mode. These parameters are loaded via a configuration file at startup of the application. Application specific parameters can be defined in another configuration file. In our application this configuration file defined the timing constraints for double taps, activation of different output modalities (audio and braille) and the dimension of the map. Next, different parsers read the map information in order to create the interactive map scenery.

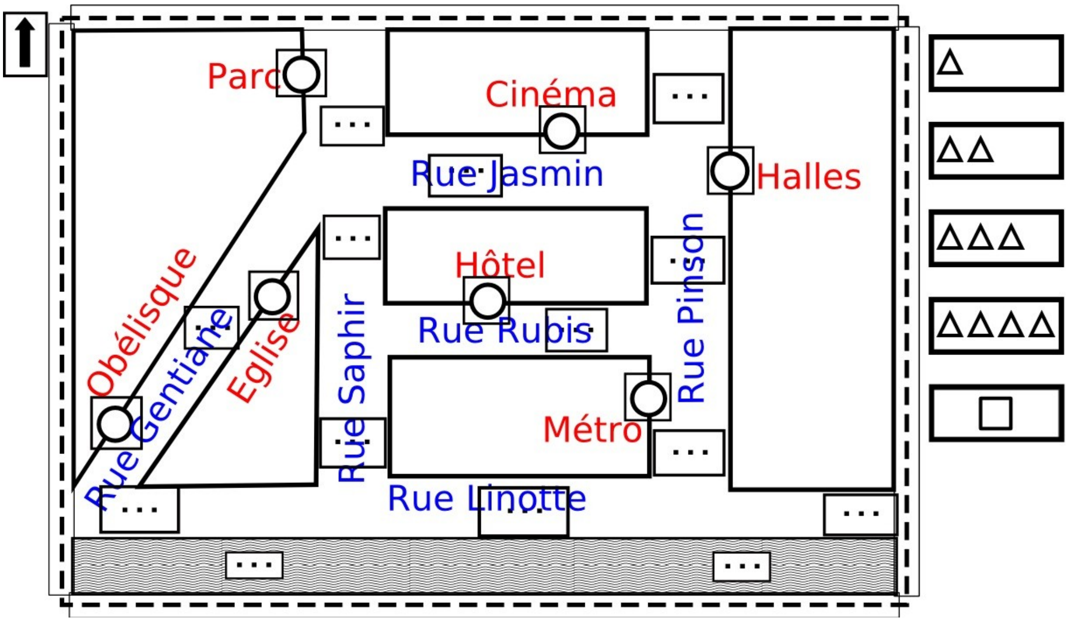


Figure V.14: View of the interactive map created as MT4J scene graph. Names of streets are depicted in blue, names of points of interests in red. All names are in French. Reprinted from (Paoleschi, 2012).

As in the previous prototypes, we designed the map with Inkscape in SVG format. As stated before this format provides a textual interface that can be analyzed by a file parser. In our application, a file parser was in charge of converting the SVG map into components in the Java scene graph. We used the SAX API[50] (Simple API for XML) for implementing a file parser. This API permits to define which markups within the SVG should be parsed for. The SVG file allowed extracting information on position and dimension of map elements. Each interactive map element was then represented as a component in the scene graph. It possessed an identifier and coordinates. One geographic element could be represented by different components. For instance, streets possessed interactive markers before and after each crossing (see Figure V.14). A component was created for each interactive marker. Figure V.14 shows the resulting view of the scene graph.

Each map was accompanied by a configuration file that provided information on the map elements. This information included name of the map element as well as supplementary information, such as opening hours, entry fees, length of a street, etc. This

[50] http://www.saxproject.org/ [last accessed June 7th 2013]

configuration file was written in XML and read with a JDOM[51] parser. JDOM charges the entire XML file into a data structure which can then be manipulated. In our prototype the information was then associated with the components in the scene graph.

V.2.1.3.e Integration of the Functionality

As stated before, it is interesting for visually impaired users to choose between several levels of information (see for instance Miele et al., 2006). We decided to make this information accessible via modes, i.e. different system states allowing different interaction technologies (Foley et al., 1996). The idea was to reduce the chance of accidentally executing gestural interaction. For instance, if the tap and hold gesture was active, a user might accidentally activate it by pressing two fingers on interactive map elements. It therefore makes sense to limit the number of active gestures for each mode. The different modes could be accessed through buttons on the map.

V.2.1.4 Preliminary Evaluations

The presented prototype is a proof-of-concept and only few tests have been done so far. The tests have been conducted with one blind researcher to check the functioning of different map features. This person had also tested the previous map prototype and was thus familiar with the interactive map concept. For the experimental setup (Figure V.11), the interactive map was positioned horizontally on the screen as in the evaluation of the previous map prototype. The braille display was placed on a table behind the screen. This allowed the users to have a comfortable hand and arm position while exploring the map. As we supposed that the braille display would be accessed only sporadically, the position of the braille display was less crucial. For making it easy to locate the braille display we placed it just behind the edge of the screen. This was in line with Kane, Morris, et al. (2011) who suggested that blind subjects used the screen borders as orientation for localizing their hands.

The pre-study revealed that audio output was comprehensible and the braille display functional. We detected that the user needed some time to familiarize with the new gestures, but was then able to use the different gestures that have been proposed for accessing different levels of information. The lasso gesture seemed to be challenging as it demanded to first identify a map element and then circle around it. This can be done more easily with the visual than with the tactile sense. There were no problems with accessing the different information levels by means of the different buttons. Also the tap-and-hold gesture for the distance worked well.

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[51] http://www.jdom.org/ [last accessed June 7th 2013]

V.2.1.5 Conclusion

In this section we implemented basic gestural interaction techniques that can be used in interactive maps for visually impaired people. Although a complete study is required to design advanced gestural interactions, we checked that it was possible for a blind user to access fundamental information (i.e. distance) and navigate different modes and levels of information via gestural interaction. Furthermore we observed that gestural interaction should be picked carefully. Gestures like the lasso that are easy for sighted people may be less evident for visually impaired people. This finding is in line with previous studies on gestural interaction for visually impaired people (Kane, Wobbrock, et al., 2011).

This work only presented a proof-of-concept and a more profound design process would be necessary for perfection. We believe that thoroughly designed gestural interaction would be important to include in a commercial prototype. For this purpose, it would be important to choose the arrangement of functionality in different modes based on ergonomic criteria and users' needs. It would also be important to verify that the chosen gestures were usable without sight. In the future, it would be interesting to go beyond the basic gestural interaction provided by the API, and to design specific gestural interaction. For this purpose it would be desirable to include visually impaired people throughout the process from the creation of ideas to the evaluation. As a concrete example, in a subsequent project we focused on the design of specific interaction techniques for route learning on interactive map prototypes.

V.2.2 Non-visual Interaction for Route Learning

Interactive maps present an overview of a geographic area. We have previously demonstrated that they help gain landmark, route and survey knowledge (see chapter IV). We have been interested in the question whether the map could be adapted with the precise aim to teach route knowledge to the users. Learning route knowledge is interesting for a visually impaired person in order to prepare a trip. From a scientific perspective this question is interesting because it demands a shift from an allocentric perspective (the map) to an egocentric perspective (the route). To our knowledge, few studies so far have investigated the possibility to represent routes guidance on interactive maps for visually impaired people. In this section we propose our approach for studying this question. The work described in the following subsections was begun during the internship of Sophien Razali under the supervision of Anke Brock.

V.2.2.1 Analyzing Route Learning Functionality in Existing Maps

Few studies within the corpus of interactive maps (see II.4) have investigated interaction techniques for route learning. Most of the studies used audio output for guidance. For example, Strothotte et al. (1996) reported that users were enthusiastic about the idea of calculating a route before traveling. In their prototype the user's finger was guided on the route through audio output. Pitch and balance were selected to convey the distance of the finger from the route. Similarly the TimbreMap provided a "line hinting mode" in which the user's finger was guided through stereo audio feedback (Su et al., 2010). The feedback faded when the user's finger left the path. In the case of the One Octave Scale Interface the user's finger was guided through musical feedback, more precisely through playing the notes of an octave (Yairi et al., 2008). Hamid & Edwards (2013) investigated a different approach. Their prototype was composed of a multi-touch screen with raised-line overlay and audio output. In contrast with other prototypes, their map was fixed on a turntable. Thus users could turn the map in order to adapt the map representation to their current egocentric perspective. No user study so far has evaluated whether this concept is successful for acquiring route or survey knowledge of an unknown area.

V.2.2.2 Designing Non-Visual Interaction for Route Learning

As in the previous development cycles we organized a brainstorming session for creating design ideas. One blind and seven sighted researchers participated in the session. The objective was to generate ideas for guiding the user's finger on an itinerary. The map prototype for which the interaction techniques should be created was the same as in previous studies, thus composed by a multi-touch screen with raised-line overlay. In contrast to some of the above mentioned existing prototypes, itineraries could therefore be displayed as relief on the raised-line map. Additional audio or haptic feedback would then be needed to indicate to the user which line to follow with his fingers, but users would automatically feel whether they touched a line or not.

Several interaction techniques were evoked. At the end of the session we selected the five interaction techniques that seemed the most promising. First, we proposed to guide a user by verbal description. This technique resembled the instructions given by a navigation system, i.e. "turn left on the next crossing". We called this technique "Guided Directions" after a similar technique proposed by Kane, Morris, et al. (2011).

Second, as an alternative verbal guidance we proposed to use the clock face method. As an example for this method, noon would suggest straight ahead, three o'clock to the east, etc. This idea was inspired by the fact that some blind people are used to the clock face method for orienting themselves in a real environment. We will refer to this technique as "Clock Face Method".

Third, we proposed using a musical interface similar to the One Octave Scale (Yairi et al., 2008). We discussed the idea of using a well-known musical piece, like for instance the beginning of Beethoven's "Für Elise" instead of playing the notes of an octave. However, choosing a musical piece seems more difficult as the musical knowledge of users depends for instance on cultural aspects or education. Also, the musical piece would have been needed to be very short in order that it could be played entirely for each route segment. We therefore decided to stick to the idea of the octave. We will refer to this technique as "One Octave Scale".

Fourth, we wanted to try the edge projection technique—a bimanual interaction technique (Kane, Morris, et al., 2011). In this technique a menu was projected to the edges of the screen. The positions of the points on the map were projected to the x- and y-axis of the edge menu. Users could thus quickly browse the menu for identifying all onscreen targets with their right and left hands. If they identified a target they could drag their fingers from the edge to the interior of the screen to locate the desired landmark (see Figure II.17). This technique appeared interesting as it was the most efficient technique in the study presented by Kane, Morris et al. In contrast to the other techniques that we proposed during the brainstorming it would not guide the user on the itinerary but rather provide decision points of the itinerary that the user would then have to mentally connect. We called this technique "Edge Projection" as in its original publication (Kane, Morris, et al., 2011).

The previous techniques were all based on audio output. However, our analysis of non-visual interaction techniques had revealed that tactile feedback is also an interesting means of non-visual interaction. Thus we wanted to explore the use of tactile interaction. Our idea was to use vibrating wristbands that had previously been developed and employed in our research group (Kammoun, Jouffrais, Guerreiro, Nicolau, & Jorge, 2012). The idea was then to develop vibrational stimulation of different length and rhythm to inform the user whether he should turn right or left. A similar concept has been employed for guiding pedestrians with a tactile compass (Pielot, Poppinga, Heuten, & Boll, 2011). We called this technique "Vibrating Wristband".

Another aspect that was evoked and needed further investigation was how to guide users in case that they missed the correct itinerary.

We also discussed that it would be interesting to provide the user with a descriptive overview of the route prior to exploring it. Even if we thought this idea would be helpful for memorizing the itinerary we did not further investigate it in this project.

V.2.2.3 Prototyping and Evaluation

As explained before (III.2.5), prototyping can be done with low- or high-fidelity prototypes. Following the brainstorming session, we decided to implement the techniques in a two-step approach: first a low-fidelity prototype to evaluate the concepts in a Wizard of Oz simulation, and then a high-fidelity prototype for user experiments. Prototyping and evaluation phase were therefore closely linked and are presented in a common subsection.

V.2.2.3.a First Cycle: Low-fidelity Prototype and Wizard of Oz

The decision to develop a low-fidelity prototype and organize Wizard of Oz sessions was made in order to provide a means for a quick evaluation of concepts before spending time on the implementation. We wanted to ensure that the concepts we had developed during the brainstorming session were understandable and usable. The insight gained during this step should help to improve interaction techniques and to propose an experimental protocol.

Map Drawing

As in the previous projects, this prototype included a raised-line drawing. In contrast with previous map drawings, we only wanted to present street information and no buildings. Moreover, we did not want to provide any knowledge about names of geographical elements. We decided to draw the streets as single lines because single lines are easier to follow with a finger than double lines (Tatham, 1991).

We based the drawing on the road network of the city center of Lille, a city in the North of France. This road network was interesting as it was quite complex and angles between streets were not necessarily rectangular (see Figure V.15). In addition, given the distance between Lille and Toulouse, we assumed that participants did not have prior knowledge of the road network. Concretely, we prepared four different itineraries which were chosen with the goal of having a similar difficulty. The blue route (Figure V.15 a) consisted of six segments with two right and three left turns. The yellow route (Figure V.15 b) consisted of six segments with three right turns and two left turns. The red route (Figure V.15 c) consisted of six segments with two right and three left turns. The green route (Figure V.15 c) consisted of six segments with two right and three left turns.

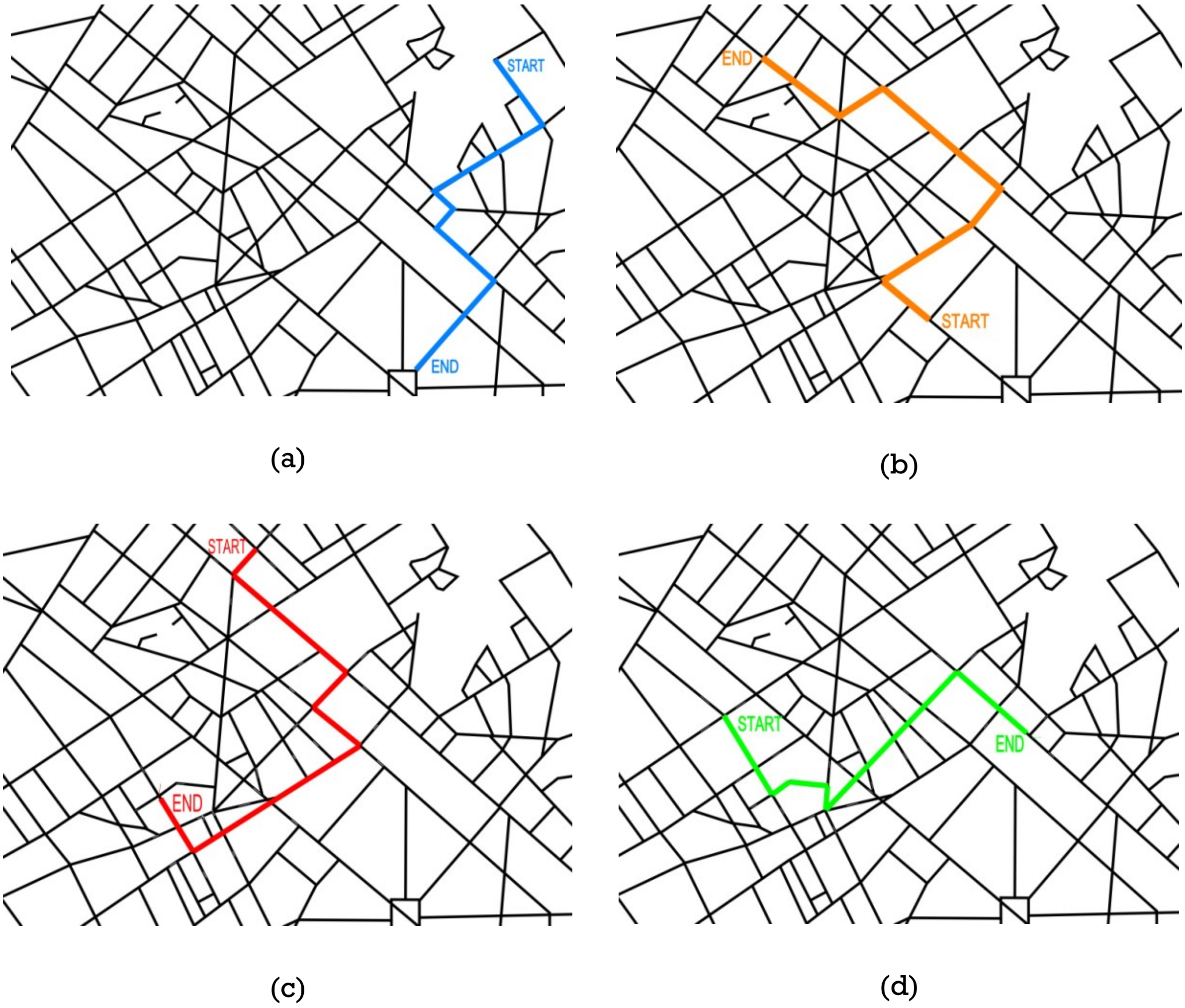


Figure V.15: Map showing the road network of Lille as used for the Route Learning Study. Four different itineraries (a, b, c, d) were prepared.

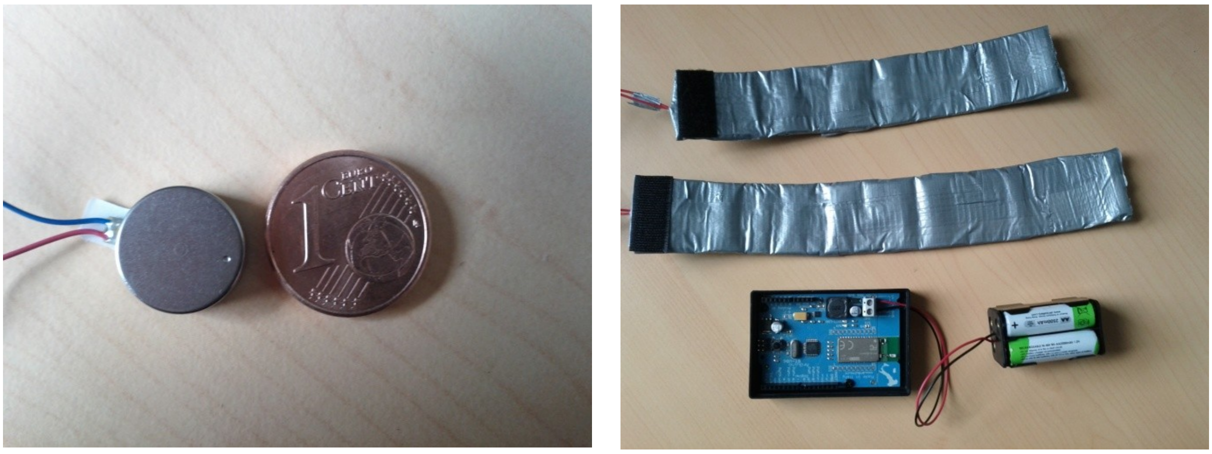
Simulated Output Modalities

The verbal guidance techniques, both "Guided Directions" and "Clock Face", needed simulated verbal output. The idea was that the experimenter observed the user exploring the map and provided speech output as live reaction to the exploratory movements. In order to make the simulation as realistic as possible the user was asked to wear headphones. The experimenter used a microphone and the audacity software[52] with the live output routed to the user's headphones. For the "Guided Directions", the experimenter announced "right" or "left" shortly before arriving at a crossing. Indications were given in the reference system of the travel (i.e., the finger). In case nothing was announced, the user was supposed to continue straight. For the "Clock Face", the experimenter announced the hour towards which the user had to turn. This hour corresponded to the map reader orientation and not to the finger. For both techniques, if the user did a wrong turn this was announced verbally.

[52] http://audacity.sourceforge.net/ [last accessed September 21st 2013]

For the "One Octave Scale" Interface we needed simulated musical output. We used a virtual midi piano for this purpose. However, simulating the output proved tricky. Indeed, the idea was that the notes of the octave were emitted in proportion with the distance that the finger had "traveled" on the map. Therefore the speed of the output needed to adapt to the speed of the finger. In order to help the experimenter, we marked the names to be played on the map next to the road. The experimenter also needed to train before doing the actual experiment. The One Octave Scale had the disadvantage that the direction for turning was not announced. Therefore at each crossing the user had to test all possible directions. Wrong turns were announced with a beep in a different octave.

The "Edge Projection" technique was altered from the original publication (Kane, Morris, et al., 2011). As we did not want to provide the names of map elements, there was no need for verbal feedback. We opted for earcons in the form of simple beeps. The user had to search for the start point of the itinerary by gliding first one, then the other finger on the edge menu. A beep was emitted when the finger matched the position of the point. When both edge points were found, the user had to connect both fingers. The system confirmed when the user found the point. It then activated the next point.



(a) (b)

Figure V.16: Photograph of the vibrating wristbands. (a) The vibration motor. (b) The haptic bracelets with Arduino board. Reprinted with permission from (Kammoun, 2013).

Finally for the "Vibrating Wristbands" technique, we used two wristbands with vibro-motors (see Figure V.16). These wristbands had been handmade in a prior project in our research group (Kammoun, 2013). Each band contained one vibration motor VPM2 of the brand Solarbotics[53]. The tactile interface was programmable through an Arduino

[53] https://solarbotics.com/product/vpm2/ [last accessed September 21st 2013]

Bluetooth board and vibrational patterns were defined and uploaded once (left, right, both). The bands provided the possibility to control frequency, duration and interval between vibrational stimuli for each wristband. We made use of a previously developed smartphone application that permitted to execute vibration signals via bluetooth. Wrong turns were indicated by both wristbands vibrating at once.

Pretests

We conducted pretests so that the experimenter could train for the Wizard of Oz Sessions. Several results emerged from these pretests that required modification of the experimental protocol.

First we observed that it was necessary to follow the itinerary twice. Our protocol did not foresee a familiarization phase for getting used to the interaction technique. After exploring the itinerary once, participants were not capable of remembering the route. We therefore suggested following the same route twice, once for getting used to the technique and the second time for learning the route.

Furthermore we observed that the "Edge Projection" technique did not work for learning the itineraries. In contrast to the other interaction techniques in our study, "Edge Projection" did not continuously guide the users' fingers on a route but taught them connection points that needed to be mentally connected. The "Edge Projection" technique being a bimanual technique, users had to remove hands from the last position. It was then hard for them to remember the point that they had learnt before. In the study by Kane, Morris, et al. edge projection had proved successful for finding landmarks on a map. However it appeared less well adapted for learning itineraries. Consequently, in this study we decided not to investigate "Edge Projection" any further.

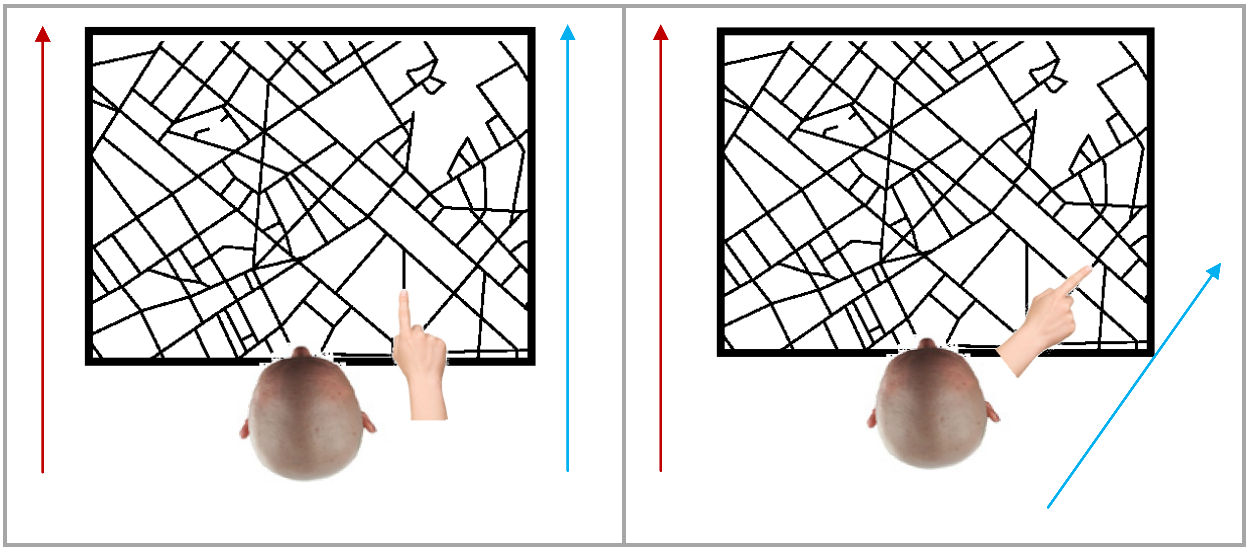


Figure V.17: Perspectives of the user (red) and the traveler as represented by the finger (blue). (a) Orientations are aligned. (b) Orientations are misaligned.

Finally, participants had problems to react to the vibrational stimulation. Users were supposed to turn the finger to the left on the next crossing when the left bracelet vibrated and vice versa. However the egocentric perspective of the traveler (represented by the finger on the map) was misaligned regarding the egocentric perspective of the map reader (see Figure V.17). As reported before (II.3.2.1), map reading is especially difficult in the case that rotation needs to be applied. This means that the direction information perceived by the vibration on one of the hands, needed to be translated into the traveler's egocentric perspective. It was especially tricky that both were perceived or felt with different parts of the same body. In order to avoid left-right ambiguity between the two reference systems we decided to represent vibrations on a single wristband as tactons, i.e. distinct vibrational patterns (see II.4.4.2). A short vibration followed by a pause and a long vibration indicated to turn the finger left, a long vibration followed by a short vibration indicated to turn right and three short vibrations indicated that a wrong turn had be taken.

Participants

We recruited six sighted university students as participants (see Table III.2). Age varied between 21 and 23 with a mean of 21.83 (*SD* = 0.98). All but one participants were male. The female participant was also the only left-handed one. Participants were blindfolded during the experiment.

Table V.1: Participants in the Wizard of Oz study. Means and standard deviations are reported in the two rightmost columns. SBSOD: Santa Barbara Sense of Direction Scale.

	User 1	**User 2**	**User 3**	**User 4**	**User 5**	**User 6**	**Mean**	**Standard Deviation**
Age	23	23	21	21	21	22	21,83	0,98
Gender	Male	Male	Male	Female	Male	Male		
Handedness	Right	Right	Right	Left	Right	Right		

Procedure

In order to compare usability of the four remaining interaction techniques (Guided Directions, Clock Face, One Octave Scale and Vibrating Wristbands) we organized Wizard of Oz Sessions.

Users evaluated the system in individual sessions. The sessions took place in the laboratory ULYSS in the IRIT research laboratory in Toulouse, France. Video was recorded after agreement from the participants.

On arrival in the laboratory participants were informed about the aim of the study, i.e. testing different applications for guiding the user on an itinerary on an interactive map. In order to motivate them, the experimenter introduced a scenario in which they had to prepare a holiday trip to an unknown city (similar to the scenario in the experimental study of the interactive map, see IV.2.3.3.a). As the blindfolded sighted participants were not used to tactile map reading, they were then allowed to familiarize themselves with the raised-line map. They did not get any audio information on map content or itineraries but if necessary the experimenter helped them to follow the raised lines. Once the participants felt comfortable with the map representation, the experimenter introduced the task which consisted in following the guiding instructions and memorizing the itinerary (see Figure V.18). Every user tested four different conditions. For each condition the experimenter first described the technique. Users were informed in advance that they would be asked to reproduce the itineraries. The users could then try the technique twice. Afterwards, they had to answer a SUS questionnaire. We also collected qualitative feedback. The same procedure was then reproduced for the three other conditions.

Figure V.18: A participant while following the route guidance (with the right index finger).

Observed Variables

The independent variable in our study was the type of interaction technique which was designed as within-participant factor. As the four itineraries possessed an equal number of segments and turns we did not expect an impact of the itinerary on the result. The different interaction techniques were crossed with the four different itineraries. The order of presentation was randomized to prevent effects of learning or fatigue.

We measured usability of the interaction techniques as efficiency, effectiveness and satisfaction. Efficiency corresponded to the time between the start and the end of following an itinerary. Effectiveness was determined as number of errors. We defined an error as the participant not following the instructions of the application (for instance turning left when right was indicated). Obviously, there is a difference between One Octave Scale and the other techniques, as One Octave Scale does not indicate in which direction to turn. The user has to explore each direction at the crossroad. An error was counted when he/she continued in a direction even if the "wrong turn" sound was emitted. Satisfaction was measured with the SUS questionnaire. We used the questionnaire from the experimental study (see IV.2.3.4.b) with minor adaptations (for instance renaming "map" in "technique"). The questionnaire is presented in the appendix (VII.9.1).

Results

We have hypothesized that interaction techniques would differ in exploration time, number of wrong turns and satisfaction, without specifically favoring any of the techniques. Therefore we investigated the four techniques with regard to the different aspects. An alpha level of .05 was used for statistical significance in every test.

Exploration Time (Efficiency)

Exploration time was measured for the first and the second exploration. The observed time values for the first iteration were not normally distributed (Shapiro-Wilk W = 0.88, p = .03). The comparison across type of interaction technique in a Friedman test was not significant ($X^2(6) = 0.93$, p = .82).

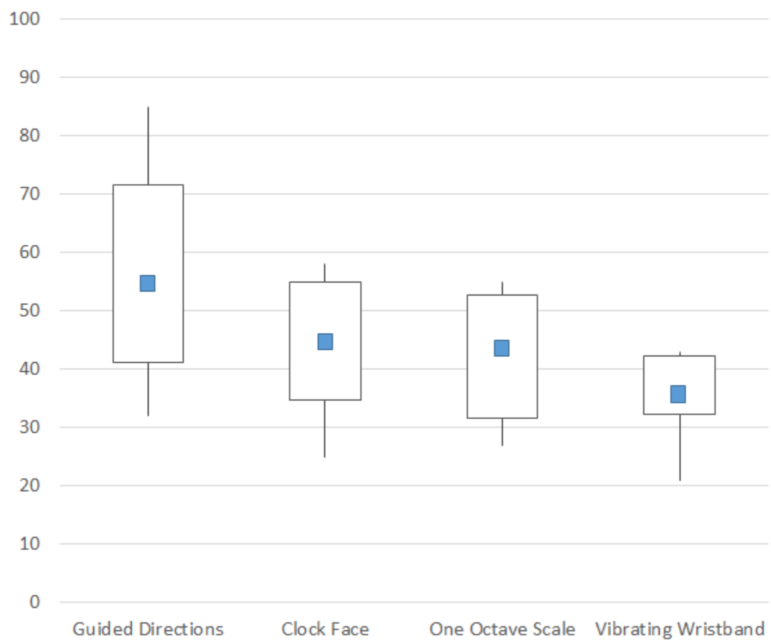


Figure V.19: Boxplot (25 – 75% interval, minimum and maximum value) of the second exploration time for both explorations taken together for the four different interaction techniques. The blue dots represent the median.

The time values for the second exploration were normally distributed (Shapiro-Wilk W = 0.95, p = .29). Accordingly they were compared across type of interaction technique in an analysis of variance (ANOVA). The effect was almost significant (F(3,15) =

2.63, $p = .09$). Figure V.19 reveals a tendency with the "Vibrational Wristband" being the quickest and the "Guided Directions" being the slowest technique.

The distribution of time values was not normal (Shapiro-Wilk $W = 0.92$, $p = .005$). The result of the Friedman ANOVA was not significant ($X^2(12)=4.22$, $p = .23$).

Errors (Effectiveness)

As for the time, errors were measured for the first and the second exploration. Errors for the first exploration (Shapiro-Wilk $W = 0.70$, $p < .001$), for the second exploration ($W = 0.78$, $p < .001$), as well as for both explorations taken together ($W = 0.73$, $p < .001$) were not normally distributed. Therefore all errors were analyzed in a Friedman test across type of interaction technique.

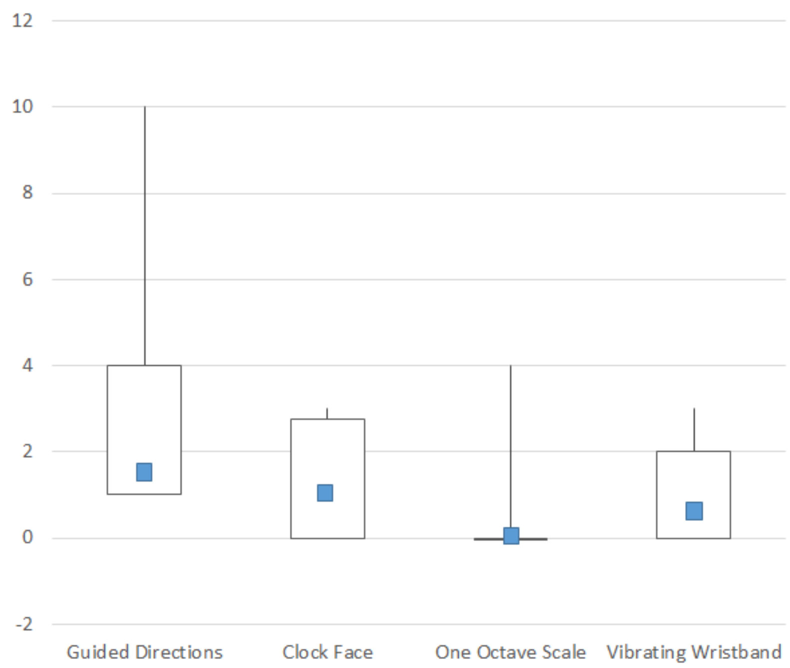


Figure V.20: Boxplot (25 – 75% interval and maximum value) of the errors for both explorations taken together for the four different interaction techniques. The blue dots represent the median.

For the first exploration the Friedman test was not significant ($X^2(6) = 4.92$, $p = .23$). The Friedman test for the second exploration revealed significant results ($X^2(6) = 10.35$, $p = .016$). Similarly, for error values taken together there was a significant result ($X^2(12)=13.97$, $p = .03$). Techniques ranked in the order from the best to the most erroneous were One Octave Scale, Vibrating Bracelets, Clock Face and Guided Directions (see Figure V.20). Pairwise Wilcoxon rank sum tests with Bonferroni correction (alpha level = .0125) revealed that only the difference between Guided Directions and One Octave Scale was significant ($N = 11$, $Z = 2.93$, $p = .003$).

Satisfaction

Satisfaction was measured with the SUS questionnaire. The results of the SUS were not normally distributed (Shapiro-Wilk W = 0.91, p = .04). Therefore the values were compared across type of interaction technique in a Friedman test. The result was almost significant ($X^2(6) = 6.41$, $p = .09$). Figure V.21 shows a tendency with the One Octave Scale receiving the best satisfaction values, and the Clock Face receiving the lowest satisfaction.

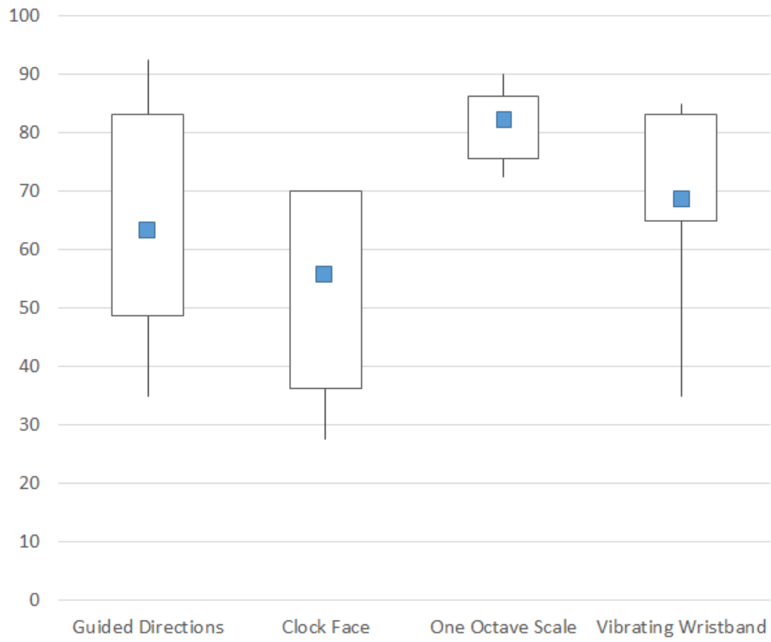


Figure V.21: Boxplot (25 – 75% interval, minimum and maximum value) of the results from the SUS questionnaire for the four different interaction techniques. The blue dots represent the median.

We also asked participants which interaction techniques were their favorite and their least preferred. The One Octave Scale was ranked five out of six times as favorite technique. One participant liked the Guided Directions most, and one of the participants that had stated a preference for using the One Octave Scale said that the Guided Directions were better for memorization. Three participants stated that they least liked the Clock Face and two participants stated that they disliked the Guided Directions. One participant did not have a technique that he disliked most.

Discussion

The presented study was part of an internship and thus limited in time. As expected due to the low number of participants, the study revealed few statistically relevant results. Yet, we were able to detect some tendencies. Of course these tendencies have to be considered with caution but we will take them as a basis for a more detailed user study that is currently in preparation. More precisely, the outcome allows reflecting on each of the different interaction techniques.

One Octave Scale

The only prototype within the interactive map corpus that used musical output (seeII.4.4.1.c) was the One Octave Scale interface (Yairi et al., 2008). Our study suggests that it might be without good reason that this interaction technique has not been further investigated. In our Wizard of Oz simulation the One Octave Scale interface was the one with the least number of errors. It was also the one that most participants preferred.

All users stated that the technique allowed a good estimation of the total distance of the segment. One user specifically stated that he could estimate the remaining distance and slow down before arriving at a crossing. However, several users stated that the system was missing an indication for the next direction. Propositions for indicating directions included using stereo sound, playing different musical pieces depending on the next direction or playing one specific note just before arriving at the crossing.

Vibrating Wristbands

Our interest in using vibrational feedback had been piqued by the analysis of non-visual interaction techniques in existing interactive map prototypes (see II.4.4.2). In the present study the use of tactons (Brewster & Brown, 2004) proved efficient. Indeed for the second exploration, there was a tendency for the Vibrating Wristbands being the quickest interaction technique. The data suggest that there was a learning effect between the first and the second exploration. As stated before, understanding tactons is not innate and has to be learnt (see II.4.4.2). Yet, our results suggest that in case of a small number of patterns that are easy to distinguish, tactons can become a powerful means of interaction.

Three users stated that they would prefer to have two wristbands, which contradicted the findings from our pretests. Another participant suggested a different coding for the tactons (one long: turn right; two short: turn left; three short: wrong turn). In addition, one user suggested adding a signal for “continue straight”. Several users stated that they needed to concentrate during this technique. One user underlined that the technique was difficult but because he needed to concentrate he made less errors.

Clock Face

The Clock Face method had the worst results in the SUS questionnaire. It may be hypothesized that this is because we tested with sighted people who do not normally orient themselves with the help of the clock face. Therefore we suppose that with visually impaired people we might have obtained better results.

Unsurprisingly, one participant stated that he had problems linking hours and directions. Another participant stated that this technique did not foster a good memorization. On the other hand, one user stated that this technique was the most intuitive (however he preferred the One Octave Scale Interface). A different user stated that the system was handy at crossings with more than four streets because it allowed indicating precise directions.

Guided Directions

The Guided Directions was the technique with which users made the most errors. However, this was not represented in the satisfaction, which was better than for the Clock Face Method. We suggest that the users liked this technique as it relied on familiar guiding instructions as in navigation systems or when guided by another person. We suggest that the bad results concerning error rate occur from a change in perspective. Indeed, the misalignment of the map reader's perspective and the traveler's perspective as explained above (Figure V.17) also occurs for this interaction technique.

As expected, three users stated that the instructions were natural and easy to follow. On the other hand, one user stated that the instructions were not sufficiently precise at intersections of several streets. There was no qualitative feedback that explained the higher error rate.

V.2.2.3.b Second Cycle: Implementation and Evaluation

The objective of the second cycle was to evaluate high-fidelity prototypes of the different interaction techniques. With these prototypes, we aim at obtaining more detailed data from a user evaluation.

Implementation

The results of the Wizard of Oz study have confirmed that the development of the four different interaction techniques is indeed interesting. We know have the hypothesis that the One Octave Scale technique or the Vibrating Wristband might be the most usable techniques.

In the implementation of these techniques as in the interactive map with gestural interaction (see V.2.1) we used the Multi-touch for Java (MT4J) API. For integrating Text-To-Speech in the Guided Directions and Clock Face interaction techniques, we used the

Talking JavaSDK by CloudGarden[54]. Again, as in the experimental interactive map prototype (III.2.5.3.b) the voice was "Virginie" (Scansoft). Notes for the One Octave Scale Interface were registered in advance as wav files. As for the Wizard of Oz Sessions, the tactons were defined and uploaded on the Arduino board in advance. Commands were then sent via bluetooth to activate the specific pattern for the vibrating wristbands (right turn, left turn, wrong way).

As in the previous prototypes, the maps were designed in svg format with inkscape. Thus, the segments of the different routes could be tagged with specific labels that were then parsed in the code. A config file provided the possibility to select the designated itinerary in advance to compiling and executing the code. Only this itinerary was then interactive during the exploration of the map. In addition to the map for the Wizard of Oz study, we introduced four new itineraries. This was done so that a familiarization phase could be added to the protocol.

Evaluation

We plan to conduct an extensive user study to evaluate the different interaction techniques. Several interesting perspectives emerged from the Wizard of Oz study.

First, we plan to investigate whether tactons could be the most efficient interaction techniques. We hypothesize that including more participants in the study might reveal significant effects.

Furthermore we believe that the results of the Clock Face Interface would have been different when testing with visually impaired people. It would therefore be interesting to include both sighted and visually impaired participants in order to evaluate whether their preferences differ. Few studies so far have investigated differences between sighted and visually impaired users concerning non-visual interaction.

Qualitative feedback from participants in the Wizard of Oz simulation also suggested that the One Octave Scale might be even more powerful if directional information could be included.

Furthermore, we also plan to include evaluations of the resulting cognitive maps with methods as proposed in section II.2.2.5. An interesting aspect concerning spatial cognition is the misalignment of orientation between the finger and the map reader, which may be the reason for the higher error rate for the Guided Direction technique. It would be very interesting to further investigate this aspect. It would also be interesting to

[54] http://www.cloudgarden.com/ [last accessed September 21st 2013]

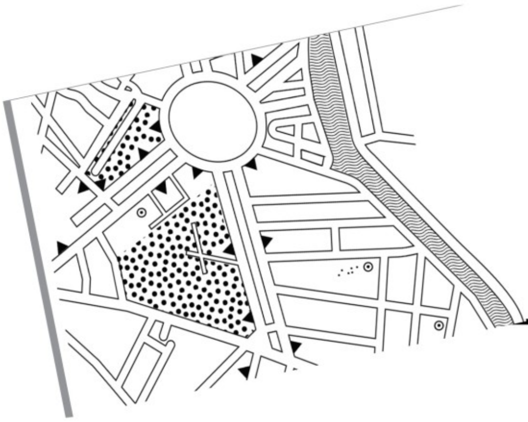
study whether using a tangible object as representation of the traveler on the map improves spatial cognition. In contrast with the finger, a tangible object is external to the observer's body, and also the object can be chosen so that it has a clear indication of direction (for instance an arrow indicating direction). Finally, the objective of route learning is to successfully navigate in a real environment and for this purpose egocentric knowledge is needed. It would therefore be desirable to study whether the presented interaction techniques successfully allow the transfer from an allocentric to an egocentric perspective. In fact, it can be hypothesized that the Guided Directions technique is best adapted for this task as the user memorizes the direction of turning at a crossing. Evaluating the navigation skills in a real environment after learning of routes with the help of the interactive map, may therefore be envisioned.

V.3 Conclusion

In this chapter we investigated Research Question 4 (How can non-visual interaction enhance tactile map exploration?). We presented preliminary investigations with the purpose of opening up avenues for future work. More precisely two sub-questions were studied.

First, we proposed the Kintouch prototype with the goal of better understanding how visually impaired people read tactile maps. The prototype was composed of a multi-touch screen and a Kinect camera. Fusion of data from both sources allowed tracking finger movements during raised-line map reading. Preliminary evaluations suggest that this technology could be helpful for studies on haptic exploration strategies, even if further development would be needed. We suggest that a better understanding of haptic exploration strategies would be helpful to design interaction techniques that are truly accessible and usable.

Second, we aimed at exploring the use of advanced non-visual interaction to include further functionality in the maps. So far few interactive map prototypes make use of gestural interaction. We explored the possibility to include basic gestural interaction (lasso, tap and hold) into our interactive map prototype. The aim was to provide supplementary information such as distances or details on specific landmarks. Preliminary studies suggest that gestural interaction can be successfully used by visually impaired people. Furthermore, we wanted to study in more detail how to design precise interaction techniques for route learning with the help of the interactive map. Four interaction techniques have been evaluated in a Wizard of Oz simulation. The One Octave Scale technique proved to be highly appreciated and faultless. Results also suggest that tactons may be a highly efficient means of non-visual interaction. Furthermore, we suspect a problem of transfer between the different perspectives of the map reader and the traveler. The four interaction techniques have been implemented. We propose possible investigations for a user study that we plan to do in the near future.



Chapter VI

Discussion and Conclusion

VI Discussion and Conclusion

This chapter summarizes the research and states our contributions. It illustrates how the work conducted in this thesis answers the four research questions that have been positioned in the introduction. Based on this, we discuss how the contributions validate the thesis statement. Several directions for future work have emerged and are discussed.

VI.1 Thesis Summary

This doctoral research investigated the design and usability of interactive maps for visually impaired people and the impact of these maps on spatial cognition.

Chapter I defined the context and the scope of the research. We situated the research in the field of accessible geographic maps for sight impaired people, and more precisely in the field of interactive maps. We also presented four research questions that we addressed in the following chapters, as well as the methodology of the thesis.

In chapter II we presented the theoretical background of our work. We first defined and classified visual impairment and stated its impact on spatial cognition. We underlined the large heterogeneity among visually impaired people and stated that several factors such as the proportion of lifetime with blindness influence perception and cognition. Second, we presented research on spatial cognition for sighted and visually impaired people. We defined cognitive maps as comprehensive representations of the environment created from sensory and motor input and containing different types of spatial knowledge. Different sources of sensory and motor input can lead to these representations. Thus the literature suggests that visually impaired people are capable of acquiring spatial knowledge but that this process works differently. We also presented methods for evaluating spatial knowledge without sight. Then, we discussed maps as tools for cognitive mapping. We demonstrated the benefit of raised-line maps for the spatial learning of visually impaired people. We also presented how these maps are produced. Furthermore, we underlined that raised-line maps possess certain limitations which can be overcome by interactivity. We presented a classification of accessible interactive maps with regard to non-visual interaction, including devices, input and output interaction. We stated the interest of accessible touch input—especially gestural interaction—and speech recognition for accessible maps. On the output side, different audio and touch interaction techniques have been presented. We underlined the interest of combining different output modalities for improving performance. Finally, we presented user studies that have been done with the interactive map prototypes.

Chapter III treats two questions: the design of an interactive map and the adaptation of the design process to include visually impaired participants. First, the map was composed by a multi-touch screen, a raised-line map overlay and speech output. For each map component we presented different versions that have been developed through an iterative process. Second, we based our work on a participatory design process in four steps (analysis, design prototyping and evaluation). As the methods of participatory design mostly rely on the visual sense we needed to make it more inclusive for visually impaired people. We proposed several recommendations to this regard (VII.7).

In chapter IV we focused on the usability of an interactive map prototype as compared to a raised-line map. We conducted a study with 24 blind participants to investigate this question. Our study did not reveal any differences concerning spatial cognition but a significant advantage of learning time and user satisfaction for interactive maps. Furthermore, we studied spatial cognition in more detail. We did not observe any effect of the map type on long-term spatial cognition. Yet, we observed significant differences for the three types of spatial knowledge (landmark, route and survey) both at short- and at long-term. We also observed that personal characteristics influenced the result. Specifically we observed that users with low braille reading skills benefited from interactive maps.

Finally, in chapter V we investigated how interactive maps could further be enhanced. More precisely we studied two sub-questions. First, we suggested that better understanding visually impaired people's haptic exploration strategies would be helpful to design interaction techniques that are accessible and usable. For this purpose, we proposed a prototype—based in a multi-touch screen and the Kinect. Second, we investigated the use of advanced non-visual interaction for including advanced features into the map. With regard to this question, we investigated the possibility to include basic gestural interaction (lasso, tap and hold) into our interactive map prototype. Furthermore, we designed four interaction techniques for route learning on an interactive map prototype. The One Octave Scale technique proved to be highly appreciated and faultless. Results also suggest that tactons may be a highly efficient means of non-visual interaction. We conclude with propositions for further user studies.

VI.1.1 Research Questions

In the introductory chapter (I), we presented four research questions to address the thesis statement. This section presents the answers to the research questions.

VI.1.1.1 Research Question 1

This question was split in two closely linked parts to which we replied successively.

- What is the design space of interactive maps for visually impaired people?
- And what is the most suitable design choice for interactive maps for visually impaired people?

In chapter II, we opened the design space. We included 43 articles published over the past 26 years in the corpus of interactive maps. These articles were analyzed with regard to devices, modalities and interaction techniques (a supplementary analysis regarding origins of the projects, timeline and map content is provided in the appendix VII.5). Various devices have been used in existing prototypes. We classified the devices in four categories according to common principles of input sensing and representation of information: haptic devices, tactile actuator devices, touch-sensitive devices and other. With regard to input interaction we presented speech recognition and touch input (including accessible gestural interaction). On the output side, different audio and touch interaction techniques have been presented. Audio output is not limited to speech, even if it is very often employed in assistive devices for visually impaired people. Auditory icons, earcons, music and spearcons provide alternatives. We suggested the use of ambient sound, earcons or music to provide complementary information to speech. In some prototypes, audio output is provided in 3D which appears to be an interesting possibility. Our analysis revealed that most existing projects combined different modalities. There is also evidence for a better performance if more than one output modality is provided. Touch output can be cutaneous, kinesthetic or haptic. We discussed the possibilities provided by vibro-tactile output, raised-pin displays, laterotactile displays. We underlined the importance of a fixed haptic reference frame for the creation of a cognitive map. We argued that raised-line map overlays are highly adapted for presenting spatial information to visually impaired people. First, they rely on previously acquired map reading skills. Second, they also provide a fixed reference frame.

In a second step we designed our own interactive map prototype. As conclusion of the previous analysis of existing interactive maps, we suggested that the best design was based on a multi-touch table with a raised-line map overlay and speech output.

Specifically we focused on the context of exploration of an unknown geographic area for visually impaired people in an "immobile" situation. We developed the system's components in an iterative process. For instance, we prepared several versions of the map drawing. We presented two possible software architectures. Several pretests helped us improve the design. Finally, we developed a high-fidelity prototype for a user study based on the 3M™ Multi-touch Display M2256PW, modular software architecture, double tap touch interaction, and a TTS.

Based on the experience of designing interactive maps we can propose guidelines for the different map components (see VII.6.3).

VI.1.1.2 Research Question 2

- How to involve visually impaired people in a participatory design process?

Participatory design methods are often based on visual modalities. In this project we have demonstrated that it is possible to make the process itself accessible to include visually impaired people. Concretely, we have applied a design process in four steps: analysis, generation of ideas, prototyping and evaluation. Participants in our project have been involved from the start to the end of the project. From this experience we can give several recommendations (see VII.7)

The approach presented above helps to make participatory design more accessible. Yet, there is still room for improvement. We call for the development of new technologies to improve the accessibility of the design process. For instance accessible CSCW (computer supported collaborative work) tools could be used in brainstorming in order to share ideas between visually impaired and sighted participants. To this end, we would hope to see more accessible design projects in the future.

In our project, participants have been involved all along the process. Yet, prototypes were created with the users as "consumers" and not as "designers". It would be interesting to include users even closer and let them design their own prototypes. This however demands, that users become experts of the technology that is used.

VI.1.1.3 Research Question 3

- How usable is an interactive map in comparison with a tactile paper map?

In this thesis we presented a study with 24 blind users. The objective of the study was to compare the usability of an interactive map and a paper map, both designed for visually impaired people. We expected a higher usability for the interactive map: more precisely we expected a better spatial learning (effectiveness), shorter learning time (efficiency) and higher user satisfaction. This hypothesis was partially confirmed: we did not observe any differences with regard to spatial learning, but learning time was significantly shorter for the interactive map and more users preferred the interactive map over the paper map. Furthermore, the interactive map was accessible to a blind person with low braille reading skills that could not read the raised-line map. Indeed, satisfaction for the use of interactive maps proved to be independent of age-related factors, whereas braille reading experience and proportion of lifetime with visual impairment were correlated to satisfaction for reading the paper map.

More precisely, we also gained insight into spatial learning. Spatial knowledge was measured at short-term (directly after exploration) and at long-term (two weeks after exploration). Our study revealed that the map type did not influence spatial learning neither at short- nor at long-term. The absence of a significant effect in effectiveness between the two maps is probably related to the small number of elements that were presented on the maps. We suggest that maps with a greater complexity might really benefit from interactivity. Significant differences in effectiveness emerged according for the three types of spatial knowledge (landmark, route and survey). At short-term landmark knowledge was significantly superior to both route and survey knowledge. In contrast, at long-term survey scores were significantly more prevalent than landmark and route scores. Furthermore we observed an impact of personal characteristics on spatial knowledge. Spatial scores for both maps were strongly correlated with self-evaluated expertise in reading tactile images. Interestingly the learning of landmarks was improved if the interactive map was presented before the paper map. We suggested that first exploring an interactive map might remove apprehension, increase map learning skills, and thus help read any kind of map at a later moment.

To our knowledge this is the first study that systematically addressed the comparison of an interactive map with a raised-line map with braille. The result of the study is of course limited to the specific type of interactive map (multi-touch screen, raised-line overlay and speech output) and cannot be generalized to other interactive map types. Nevertheless the results are encouraging as they show that interactive maps can be designed as to support visually impaired users' spatial learning.

VI.1.1.4 Research Question 4

- How can non-visual interaction enhance tactile map exploration?

We addressed this question with three different approaches.

First, we proposed a prototype for observing visually impaired users' haptic exploration strategies. The goal was to better understand how visually impaired people read tactile maps. The prototype was composed of a multi-touch screen and a Kinect camera and data from both sources were merged for tracking finger movements during map reading. Preliminary evaluations suggest that this technology could be helpful for studies on haptic exploration strategies. We suggest that this knowledge would be important to design interaction techniques that are truly accessible and usable.

Second, we explored the possibility to include gestural interaction into our interactive map prototype. Concretely, we used basic gestural interaction (lasso, tap and hold) to provide supplementary information such as distances or details on specific landmarks. Preliminary studies suggested that gestural interaction could be successfully used by visually impaired people.

Additionally, we wanted to study if precise interaction techniques for route learning could be designed. Four interaction techniques have been evaluated in a Wizard of Oz simulation. A musical interaction technique proved to be highly appreciated and users performed well with this technique. Results also suggest that tactons may be a highly efficient means of non-visual interaction. The four interaction techniques have been implemented. We propose possible investigations for further user studies.

VI.1.2 Thesis Statement

At the beginning of this thesis, we posited the following thesis statement:

Interactive maps are accessible and pertinent tools for presenting spatial knowledge to visually impaired people,
they are more usable than raised-line paper maps
and they can be further enhanced through advanced non-visual interaction.

This statement has been addressed and verified through this research. It is answered through the four research questions, as discussed in the previous section. In summary, interactive maps have proved to be accessible tools for presenting spatial information to visually impaired people. In a direct comparison with raised-line maps we have observed an improved efficiency and satisfaction, whereas we have not found any differences in effectiveness. Preliminary studies show that advanced non-visual interaction can enable the access to new features and more detailed information.

VI.1.3 Contributions

This thesis makes the following principal and secondary contributions to research in the field of HCI.

VI.1.3.1 Principal Contributions

- Comprehensive classification of non-visual interaction in interactive maps for visually impaired people.
- Design of an interactive map prototype (based on a multi-touch device, raised-line map and speech output).
- Recommendations for making the participatory design process accessible for visually impaired people.
- Evaluation of the usability of an interactive map prototype in comparison with a raised-line map with braille.
- Analysis of the spatial knowledge obtained by exploring different map types.

VI.1.3.2 Secondary Contributions

- Guidelines for the design and development of interactive maps for visually impaired people.
- Design proposition of a tool for improving the knowledge about haptic exploration strategies of visually impaired people.
- Proof-of-concept for integrating gestural interaction into an interactive map.
- Design propositions for interaction techniques for route learning with the help of an interactive map prototype and preliminary evaluation results.

VI.2 Future work

This section presents a discussion of some research opportunities and ideas for future work that this thesis work has revealed.

VI.2.1 Non-Visual Interaction for Visually Impaired and Sighted People

The field of non-visual interaction is very broad. In this thesis we focused on non-visual interaction in the context of interactive maps for visually impaired people. Therefore we only analyzed the corpus of interactive maps for visually impaired people regarding the interaction techniques that have been employed. Yet, while non-visual interaction—or eyes-free interaction—has traditionally targeted blind users, it is becoming common across a wide range of contexts. Motivations for eyes-free interaction include environmental, social, device related and personal characteristics (Yi, Cao, Fjeld, & Zhao, 2012). As an example, mobility may cause a situational handicap and call for the use of non-visual interaction techniques, as the user may not be able to watch the screen while riding a bike, driving a car or when bright sunlight is reflecting on the device. To this regard, Newell and Gregor (2000) spoke of ordinary and extra-ordinary human-computer interaction. They drew a parallel between “ordinary” people operating in “extraordinary” conditions—for instance a sunny environment—and “extra-ordinary” people, i.e. people with special needs, working in an ordinary environment. Non-standard situations in which people use standard equipment effectively disable the user. Vanderheiden (2009) presented an overview between situation related needs and needs caused by impairment. For instance, situations in which the eyes are busy or darkness, as well as blindness require non-visual interaction. Small displays and dimly lit environments impose comparable requirements as low-vision.

Various applications require non-visual interaction, including applications for improving mobility and orientation (Heuten et al., 2008), text entry (Oliveira, Guerreiro, Nicolau, Jorge, & Gonçalves, 2011), internet browsing (Asakawa, 2005), games (Merabet et al., 2012), crowdsourcing (Bigham et al., 2010) and even photography (Harada et al., 2013).

At the ACM CHI conference 2013, we proposed a Special Interest Group on Non-Visual interaction[55] with the objective to reunite projects aimed at visually impaired people and those aimed at sighted people (Brock, Kammoun, et al., 2013). We believe

[55] The community of the SIG Non-Visual Interaction can be joined online on Facebook http://bit.ly/sig-nvi or Google Groups http://bit.ly/GG-SIG-NVI.

that it would be beneficial for all researchers in the field to work together more tightly, as challenges for non-visual interaction (NVI) seem to overlap regardless of users' abilities. We believe that one of the current research challenges is in finding out whether the problems encountered by visually-impaired people are similar to those of sighted users in "extraordinary" situations, and how these problems can be addressed to achieve a high usability and accessibility for all users.

VI.2.2 Interaction Design for Non-Visual Map Exploration

In this thesis we have analyzed different interaction techniques that have been employed in interactive maps for visually impaired people. Furthermore, our own experiments have revealed several issues related to non-visual interaction. We will discuss the perspectives opened up by this thesis in the following sub-sections.

VI.2.2.1 Touch

Touch interaction has been a prevalent technique in non-visual interactive maps. However, some challenges exist when making touch-sensitive devices accessible. Furthermore, we believe that taking into account visually impaired users' haptic exploration behavior would improve the usability of gestural interaction.

VI.2.2.1.a Challenges for Accessible Touch Interaction

An important issue concerning multi-touch interaction for visually impaired people remains to be resolved: unintentional touch interaction. While developing interactive map prototypes (III), we observed that unintended touch input presented an important problem. Contrary to sighted subjects, visually impaired users tend to explore tactile maps with several fingers in parallel (Heller, 1989). At first we had implemented a single tap interaction. Applying several fingers simultaneously resulted in many sound outputs. We observed that users had problems to identify the finger that had caused the sound. We resolved this problem by implementing double touch interaction. Furthermore, users placed the palm of their hands on the surface to have a comfortable reading position. Again, the palm in contact with the surface resulted in unintended touch interaction. We resolved this problem by letting the users wear mittens. A simple alternative would have been to turn the screen in vertical direction. However, the exploration of a vertical screen is not very comfortable and generates and effect of fatigue.

Observations on unintended touch interaction of visually impaired participants have been made in other projects. El-Glaly, Quek, Smith-Jackson, & Dhillon (2012) proposed an application for allowing blind people to read books on an iPad. They observed unintended touch input from the resting palms but also from other fingers unconsciously touching the surface while holding the device. The intended touch movement was a single finger moving over the surface in order to read the book. Because this movement was regular, they were able to track it and eliminate the unintended input. McGookin et al. (2008) suggested not to use short impact related gestures, such as single taps, because they are likely to occur accidentally. Likewise, Yatani et al. (2012) proposed implementing a double tap rather than a single tap because it is less likely to occur by chance. In their study on accessible gestural interaction, Kane, Morris, et al. (2011) suggested that placing interactive zones in the edges or corners of a device or other areas that were easily distinguishable, would reduce the likelihood to trigger this interaction accidentally.

Despite these first recommendations it remains a challenge for the research domain of multi-touch interaction to find solutions and adapted interaction techniques for visually impaired people.

VI.2.2.1.b Exploration Strategies as Basis for Interaction Design

As reported in the previous chapter (V.1), there is still a lack of knowledge on how visually impaired people use their hands for the exploration of raised-line maps. Knowing which role is played by different fingers involved in the exploration process, would enable the design of adapted interaction techniques. Thus, it might be possible to solve the above reported problems regarding accidental touch interaction. In addition, it would be interesting to know whether gestural interaction should support bimanual interaction. For instance, Kane, Morris, et al. (2013) reported that several participants tried to use their prototype with two hands, which was not foreseen and thus did not work well. If this would reveal to be a natural exploration behavior, than it should be supported by the interaction. With the Kintouch prototype we have proposed a tool for the observation of haptic exploration strategies. As reported above (V.1.2), this prototype would still need supplementary work in order to make it really exploitable. We presented the remaining work and ideas for experimentations.

More recently, we have begun working on a new study (Simonnet, Jonin, Brock, & Jouffrais, 2013). The aim of this study is to better understand which interaction techniques best support spatial learning. Kane, Morris, et al. (2011) have investigated this aspect but on a large touch table, whereas we used a tablet PC. For this purpose, we have implemented different interaction techniques with the aim to support learning of spatial information (see Figure VI.1). A first interaction technique was based on edge projection as proposed by Kane, Morris, et al. (2011). In a second interaction technique, "Single Side Menu", an alphabetic menu of list items was projected to the left border of the screen. While one finger skimmed through the list, the other finger was guided towards this destination by verbal directions (right, left, down, up). The third technique, "Spatial Regions", was inspired by the Neighborhood Browsing by Kane, Morris, et al. (2011). However, the map was separated in a regular grid, instead of adapting the size of the regions to the map content. User studies for these interaction techniques are currently ongoing. Our objective is to obtain useful insight in the design of interaction techniques for spatial learning.

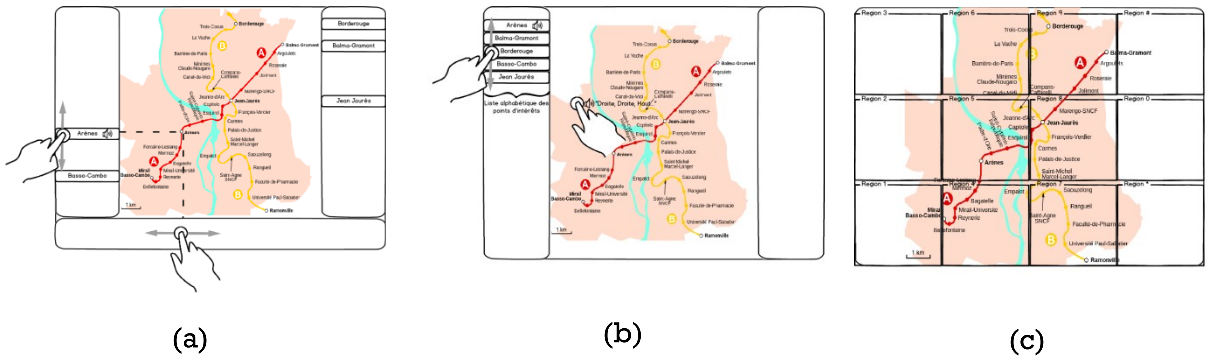


Figure VI.1: Propositions of interaction techniques for spatial learning on a tablet. (a) Edge Projection. (b) Single Side Menu. (c) Spatial Regions. Reprinted from (Simonnet et al., 2013).

VI.2.2.2 Including Alternative Interaction Techniques

The analysis of existing interactive map projects revealed that touch input and speech output are not the only promising interaction techniques. For the future improvement of our interactive maps (based on multi-touch screen, raised-line overlay and speech output) we will consider including further interaction techniques.

While studies have shown that touch was more appropriate for determining positions and forms, speech recognition is promising for certain tasks. For visually impaired people entering textual information by speech is convenient. For example, the user could enter a certain landmark ("cinema"), position the finger on the map and let the map then guide the finger to this position (right, left, up, down instructions). It could also be used for changing modes instead of button-based interaction (see V.2.1).

On the output side, non-verbal sound has proved interesting as a complement to speech. However, studies reveal contradictory results. There is a need for systematic investigation on the advantages and limitations of using non-speech audio.

So far, there has not been much research on tangible interaction with visually impaired people. Yet, first studies on tangible interaction in non-visual maps have been promising (Milne et al., 2011; Pielot et al., 2007). To this end, we have just started a research project with students from the Master 2 IHM in Toulouse (Kévin Bergua, Jérémy Bourdiol, Charly Carrère and Julie Ducasse). The aim of this project is to design and develop a multimodal prototype which allows visually impaired people and sighted people to collaboratively work on a geographic map. The prototype will be based on the use of a multi-touch table (Immersion ILight table) and tangible interaction.

VI.2.3 Overcoming Limitations of Current Interactive Maps

Several aspects have been criticized about tactile maps (see subsection II.3.3.2). We have stated in this thesis that making maps interactive can help overcome some of these limitations. For instance, the information can be updated dynamically. Also, it is possible to present more textual information than on a tactile map. Furthermore the textual information becomes accessible for people with low braille reading skills. However, in the case of interactive maps which rely on raised-line overlays some of the limitations remain valid. We will address these issues in the following sub-sections.

VI.2.3.1 Automatic Creation of Maps

One critical point is the design and production of raised-line maps which is very costly in time when it is done by hand. Rice, Jacobson, Golledge, and Jones (2005) suggested that the automatic creation of maps from Geographic Information Systems (GIS) could speed up the production. To this end, HaptoRender[56] is an ongoing project on automatic transformation of map information from OpenStreetMap (OSM) in tactile maps. This project is supported by volunteers. The use of OSM is interesting, as in 2011 it contained 30% more pedestrian roads than a commercial Geographic Information System (Neis, Zielstra, & Zipf, 2011). Among research projects, the Talking TMAP project proposed automatic map creation based on a GIS system (Miele et al., 2006). This process even included the possibility to order raised-line maps on the internet or by telephone. The user needed to possess the corresponding touch device ("Talking Tactile Tablet"), to charge a digital map and then place the map overlay on the display. However, the rendered maps only worked with very symmetric street systems, as are typical for North America. The system placed labels around the map so streets need to form symmetric crossings in order that all streets could be labeled. Consequently, Minatani et al. (2010) proposed an adaptation for Japan and other regions that worked with a more flexible street layout. In systems that do not require a printed out raised-line map, it is even easier to access OpenStreetMap (Kaklanis et al., 2013) or GoogleMaps (Bahram, 2013).

[56] http://wiki.openstreetmap.org/wiki/HaptoRender [last accessed August 13th 2013]

An alternative approach is automatic map creation based on image recognition algorithms as proposed by Wang et al. (2009, 2012) and Kostopoulos et al. (2007). Automatic map creation is challenging, as not all visual information in a map can directly be transformed to a tactile form. Thus, the two most important problems are choosing which information to keep for the final tactile presentation and how to render it in an appropriate manner (Wang et al., 2012). To this regard, Wang et al. (2009) evaluated their prototype with 6 visually impaired people. Most of the maps correctly represented landmarks and routes. Also users gave positive feedback on the clarity of information. In their later study (Wang et al., 2012) they evaluated the use of the system with 6 blind and 6 blindfolded sighted participants. The blind participants were perceived as more skillful and efficient in creating automatic maps. Overall there was a decrease of time for consecutive attempts of map creation, revealing a learning effect. Blind users rated the system as very easy, whereas sighted users complained about the software interface and output. This is unsurprising given that the system was based on the use of a screen reader which is unknown to sighted users.

VI.2.3.2 Map Annotation

Interactive maps for sighted people often include the possibility to annotate maps (for instance in GoogleMaps to write reviews). The Tactos device provided a writing function to allow users to comment graphical elements (Gapenne et al., 2003). Recently, projects have investigated whether accessible maps could be extended for collaborative use. Rice et al. (2013) proposed to make use of crowdsourcing for geospatial data collection for accessible maps. This would provide the possibility to report and locate transitory obstacles, such as roadwork. The crowdsourced map could for instance be based on the use of a haptic device (Golledge et al., 2005; Rice et al., 2005). Zeng and Weber (2012) proposed a multi-line display with raised-pins that provided the possibility to annotate maps through the screen reader. They evaluated the system with 5 visually impaired people. All subjects were able to read and create annotations in a short-time. Participants also expressed their interest in the collaborative approach of sharing location-based information. Collaborative aspects for accessible maps might be an interesting path for future investigations and will also be addressed in our above reported project on tangible interaction.

VI.2.3.3 Touch Surfaces with Tactile Feedback

Audio-tactile maps with raised-line overlays also have the disadvantage that the depicted map area is fixed. Whereas other map types allow features such as scrolling and zooming (Bahram, 2013; Schmitz & Ertl, 2010; Zeng & Weber, 2010), this is not feasible with raised-line maps. Indeed, the absence of affordable and robust tactile devices is responsible for problems related to displaying dynamic graphical information (Lévesque, 2005).

However, we argue that this disadvantage is going to be resolved in the future due to the emergence of touch-sensitive surfaces with cutaneous feedback. Laterotactile displays and raised-pin displays as presented in the classification of interactive maps (II.4.4.2), present a step in this direction. Recently further technology has emerged. In this subsection we describe some of this recent technology without the aim of being exhaustive.

Some devices produce electrostatic friction between a touch surface and the user's fingertip. Indeed, it has been shown that friction is a significant factor in touch perception. Friction feels more natural than vibrotactile feedback and provides continuous feedback (Lévesque et al., 2011). A comprehensive review on friction has recently been published by Adams et al. (2013). The principle of electrostatic friction has been used in the case for TeslaTouch (Bau, Poupyrev, Israr, & Harrison, 2010). The friction was produced without mechanical actuation but by making use of electrovibration. In electrovibration, the stimulation is only perceived when moving the finger by forming a capacitor between the finger and the surface. A periodic electrostatic stimulation applied to the surface then deformed the skin of the sliding finger. The technology is scalable to devices of any size, shape and configuration. In addition, it can be combined with touch-sensitive surfaces, so that the device provides both input and output. In TeslaTouch (Bau et al., 2010) electrovibration was created on a transparent surface which allowed to use it with a variety of devices. Concretely it has been combined with optical multi-touch technology. In a study with ten participants, it has been shown that textures with characteristics such as smoothness, fineness, gentleness or stickiness could successfully be differentiated by varying frequency and voltage. TeslaTouch has been successfully used in applications for visually impaired people (C. Xu, Israr, Poupyrev, Bau, & Harrison, 2011). It was possible to display dots and lines. Yet, it proved difficult for visually impaired subjects to recognize braille letters with this technology. A similar technology has been commercially developed by Senseg[57]. Based on their previous work, in the "REVEL" project Bau & Poupyrev (2012) reversed the principle and made the human being the carrier of the electric signal. In this technology, "reverse electrovibration", a weak electrical signal was injected into the user's body, thus producing an electrical field around the finger. By doing so, the technology became independent on hardware and any object could be augmented with tactile feedback

[57] http://senseg.com/ [last accessed September 26th 2013]

(under the condition of the object being coated with an insulator-covered electrode). Various textures could be produced by varying signal amplitude, shape and frequency.

A similar but different principle is applied in the STIMTAC prototype (Casiez, Roussel, Vanbelleghem, & Giraud, 2011). A squeeze film effect is produced by applying ultrasonic vibration with micrometers amplitude to a surface (Figure VI.2). Since the frequency is outside skin mechanoreceptors' bandwidth, users do not feel the vibration, but a "slippery" effect. The technology is incompatible with classical touch-sensitive devices and thus a custom-made sensor has been built for finger tracking. Similarly, Levesque et al. (2011) used a Large Area Tactile Pattern Display to produce a squeeze film of air. Users reported increased engagement, realism and reduced dependence on vision when interacting with this device.

Figure VI.2: Photograph of the Stimtac prototype as presented in (Casiez et al., 2011)**. Reprinted with permission.**

Other prototypes relied on magnetism. In the case of the MudPad prototype (Jansen, Karrer, & Borchers, 2010), the device was composed of an array of electromagnets containing magnetorheological fluid. The viscosity of this fluid was altered by applying a varying magnetic field. By doing so, different textures could be produced. Even if the effect was localized it could not be produced for small areas in the size of a fingertip. In the FingerFlux prototype tactile sensations were created before actually touching the surface (Weiss, Wacharamanotham, Voelker, & Borchers, 2011). For this purpose magnets were attached to the fingertip while the surface was composed of a grid of electromagnets. This technique allowed feeling forces without having to move the finger. Users could detect the signal up to a height of 35 mm.

A different approach is implemented in the Tactus technology[58] ("Taking Touch Screen Interfaces Into A New Dimension," 2012). This technology allows dynamic but physical buttons to emerge from a flat touch surface. This is done by micro-channels filled with a fluid. By increasing the pressure, the fluid presses through the holes, thus producing three-dimensional buttons.

The above presented technologies are only a selection of current technology and only a glimpse of what will be possible in the near future. Obviously, providing dynamic tactile feedback is promising for the use in non-visual interfaces and would allow new interaction techniques and functionality. We hope that as technology will improve, soon it will be possible to represent map features on such displays.

VI.2.4 Usability of Interactive Maps

In this thesis we have presented a study with 24 blind users on the comparison of an interactive map with a raised-line map. We have not fully explored the data that we have obtained from this study. Previous research indicated an effect of gender on spatial cognition (Linn & Peterson, 1985). To our knowledge no study has been done on gender-related differences for sight impaired people. It would therefore be interesting to investigate our results regarding this aspect.

Furthermore, the user study presented in this thesis possesses some limitations, which might be addresses in the future. We have made certain choices regarding the map design and the obtained positive results are limited to the specific map design (multi-touch, raised-line overlay, speech output). It would be interesting to compare the map to a map with different output modalities, for instance non-verbal sound.

Most importantly, the study did not reveal any differences regarding effectiveness (spatial knowledge). We suppose that this might be due to the limited complexity of the maps. Indeed, the readability and thus the effectiveness of a tactile map is impaired if the map contains a great number of elements and legends. In contrast, it is possible to present a richer and more complex content with an interactive map (Hinton, 1993). Therefore, it would be interesting to repeat the study with a more complex map.

Finally, in several brainstorming sessions as well as during user tests, participants have expressed their interest for ludic interfaces. Indeed, impaired people do not only

[58] http://www.tactustechnology.com/index.html [last accessed September 26th 2013]

want assistive technology, they also want this technology to be fun to use. To this end, (Merabet et al., 2012) developed computer based video games with the aim of teaching navigation skills to the blind. User experience is still rarely addressed in the field of assistive technology. It might be interesting to center future research around this area.

VI.2.5 Employment of Interactive Maps in "Real Life"

For a project in the field of assistive technology, it is also interesting to consider how this project could be employed in real life situations.

VI.2.5.1 Personal Use

For a visually impaired person who owns swell paper, a printer and a fuser, it would be possible to create interactive maps at home at a reasonable price. Yet, it would be necessary to provide the community with the digital maps and software. Some of the approaches for automatic map creation have been discussed above.

If maps could be created automatically, then the visually impaired person needed to know how to charge the digital map that belongs to the corresponding map overlay. Some approaches have been discussed in the literature In the case of the Talking TMAP project (Miele et al., 2006), a bar with vertical stripes served as identification of each raised-line map. By pressing on the stripes, the sheet was identified and the corresponding dataset loaded. Fitzpatrick and McMullen (2008) investigated the use of different technologies for this purpose. They observed that barcode readers and RFID chips both required additional hardware. As an alternative they came up with a TIN (tactile pin). The TIN corresponded to a code of tactile dots on the raised-line sheets which composed a three-digit number. The user would load a digital map on the computer and the computer would then provide the three-digit number which could be found on the corresponding raised-line map. The issue of providing digital content and according raised-line map needs to be overcome before interactive maps can largely be adopted.

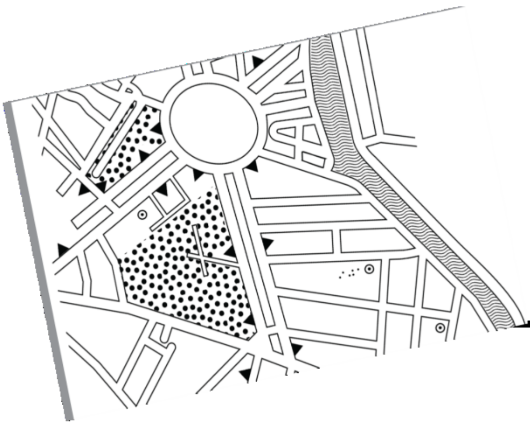
VI.2.5.2 Teaching Spatial Skills

Developing spatial skills is crucial for visually impaired people in order to achieve a degree of independence (Jacobson, 1996). Specialized Training by Orientation and Mobility (O&M) Instructors provides visually impaired people with skills for traveling autonomously. Mastering orientation and mobility demands concepts of space and environment that are not obvious for visually impaired people (Gaunet & Briffault, 2005). This includes body concepts (identifying parts of the body and knowing their locations, movements and relationships), spatial concepts (identifying spatial positions, shapes, distances, etc.), environmental concepts (features that can be found in a given environment such as traffic lights, crossroads, stairs…) and other features such as texture or temperature.

Another aspect concerns behavioral exploration strategies as described in II.2.2.4. Despite the ongoing research on these strategies, there is no conclusion on how to teach these strategies to visually impaired children. Ungar (2000) reported on a study where teaching coding strategies has not improved participant's performance. He proposed that training has to be integrated more closely with children's existing strategies and their understanding of space. He also suggested that encouraging the independent exploration of space by young blind people may facilitate their understanding for spatial structures. Another aspect in the training of spatial skills for visually impaired people concerns acquiring spatial knowledge from tactile map reading.

Given the current low prices for tablets and touch screens, it is not surprising that schools and associations for visually impaired people begin to adopt this technology for teaching. As an example, the Tact2Voice[59] project has been developed with the aim of providing visually impaired students with access to graphical data. This prototype was based on an iPad and audio output. It was destined both at blind and low vision students, as it was usable with or without a raised-line overlay. Documents were provided per mail or download and the teacher could adapt the existing material to the student's need. It would then work similarly as the prototype described in this thesis. Despite, the technological possibilities we have the impression that they are not yet systematically employed in the classroom and we believe that it would be beneficial to quickly take advantage of this technology. This is also supported by findings of our user study which suggest that exploring an interactive map before a raised-line map might remove apprehension, increase map learning skills, and thus help read any kind of map at a later moment.

59 http://bit.ly/Tact2Voice [last accessed September 26th]



Chapter VII

Appendix

VII Appendix

VII.1 List of Publications

VII.1.1 Journals

Brock, A., Truillet, P., Oriola, B., Picard, D., Jouffrais, C., Interactivity Improves Usability of Geographic Maps for Visually Impaired People (submitted to HCI, under revision)

Brock, A., Oriola, B., Truillet, P., Jouffrais, C., Picard, D. Map design for visually impaired people: past, present, and future research, in: Darras, B. & Valente, D. (éd.) Handicap et Communication, MEI 36, Paris: l'Harmattan, December 2013, pp. 117-129.

Brock, A., Touch the map! Designing Interactive Maps for Visually Impaired People, ACM Accessibility and Computing, Issue 105, January 2013, p. 9 – 14.

VII.1.2 International Conferences with Peer Review

VII.1.2.1 Full Papers

Brock, A., Oriola, B., Picard, D., Jouffrais, C., Truillet, P. Design and User Satisfaction of Interactive Maps for Visually Impaired People, International Conference on Computers Helping People with Special Needs, Linz, Austria, 2012, full paper

VII.1.2.2 Other Papers

Brock, A., Kammoun, S., Nicolau, H., Guerreiro, T., Kane, S., Jouffrais, C. SIG: NVI (Non-Visual Interaction). ACM SIGCHI Conference on Human Factors in Computing Systems - CHI, Paris, France, April 27th to May 2nd 2013, Special Interest Group.

Dray, S., Peters, A., **Brock, A.**, Peer, A., Gitau, S., Jennings, P., Kumar, J., Murray, D. Leveraging the Progress of Women in the HCI Field to Address the Diversity Chasm. ACM SIGCHI Conference on Human Factors in Computing Systems - CHI, Paris, France, April 27th to May 2nd 2013, Panel.

Dray, S., Peer, A., **Brock, A.**, Peters, A., Bardzell, S., Burnett, M., Churchill, E., Poole, E. Exploring the Representation of Women Perspectives in Technologies. ACM SIGCHI Conference on Human Factors in Computing Systems - CHI, Paris, France, April 27th to May 2nd 2013, Panel.

Brock, A., Lebaz, S., Oriola, B., Picard, D., Jouffrais, C., Truillet, P. Kin' touch: Understanding How Visually Impaired People Explore Tactile Maps, ACM SIGCHI Conference on Human Factors in Computing Systems - CHI, Austin, Texas, USA, 2012, Work-In-Progress

Brock, A., Truillet, P., Oriola, B., Jouffrais, C. Usage of Multimodal Maps for Blind People: Why and How, Proc. of ACM International Conference on Interactive Tabletops and Surfaces, Saarbruecken, Germany, 2010, Poster

VII.1.3 National Conferences with Peer Review

Brock, A., Vinot, J.L., Oriola, B., Kammoun, S., Truillet, P., Jouffrais, C. Méthodes et outils de conception participative avec des utilisateurs non-voyants, IHM'10 - ACM French-speaking HCI conference, Luxemburg, 2010, full paper

VII.1.4 Workshops

Simonnet, M., Jonin, H., **Brock, A.,** Jouffrais, C. Conception et évaluation de techniques d'exploration interactives non visuelles pour les cartes géographiques, SAGEO - atelier Cartographie et Cognition, Brest, France, September 23rd to 26th 2013

VII.1.5 Other Publications

Brock, A., Truillet, P., Oriola, B., Picard, D., Jouffrais, C., Wintergerst, G., Jagodzinski, R., Giles, P., Choi, S., Gu, J., Han, J., Heo, S., Kim, S., Lee, G., Ronchi, G., Benghi, C. Demo Hour. ACM interactions, vol. 20, nr. 1, January 2013, p.10-11.

VII.2 Glossary of Eye Diseases[60]

VII.2.1 Cataracts

Definition: Clouding that develops in the crystalline lens of the eye or in its lens capsule. It ranges from slight to complete opacity.

Symptoms:

- Blurry vision
- Early stage: the power of the lens may be increased which results in near-sightedness (myopia)
- Gradual yellowing of the lens may reduce the perception of blue colors.
- Loss of contrast sensitivity: contours, shadows and color vision are less bright.
- Potentially complete vision loss if untreated.
- Almost always one eye is affected earlier than the other.

Causes: secondary effects of diseases such as diabetes, hypertension and advanced age, or trauma; genetic factors and positive family history (for cataracts that occur at early age); long-term exposure to ultraviolet light (the increase in ultraviolet radiation resulting from depletion of the ozone layer is expected to increase the incidence of cataracts); exposure to ionizing radiation; eye injury or physical trauma; atopic or allergic conditions; iodine deficiency; specific drugs.

Propagation: Cataracts is the leading cause of blindness in the world.

VII.2.2 Diabetic Retinopathy

Definition: Damage to the retina caused by complications of diabetes. New blood vessels form at the back of the eye, they bleed and blur vision. The first occurrence may not be very severe, but may be followed within a few days or weeks by a much greater leakage of blood, which blurs vision. The blood clears within a few days to months or even years, or in some cases the blood will not clear.

Symptoms:

- No early warning signs
- Blurred vision
- The vision may get better or worse during the day
- In extreme cases: only light perception remaining
- Possible total vision loss

[60] Retrieved from Wikipedia http://www.wikipedia.org/ [last accessed January 10th 2014]

Causes: Diabetes mellitus (Type I diabetes and Type II diabetes).

Propagation: Up to 80% of all patients who have had diabetes for 10 years or more are affected. Risk increases with duration of diabetes.

VII.2.3 Glaucoma

Definition: Damage of the optic nerve in a characteristic pattern. Normally associated with increased fluid pressure in the eye and loss of retinal ganglion cells in a characteristic pattern. "Ocular hypertension": increased pressure within the eye without any associated optic nerve damage. "Normal tension" or "low tension" glaucoma: optic nerve damage and associated visual field loss, but normal or low intraocular pressure. There are many different subtypes of glaucoma.

Symptoms:

- Open-angle glaucoma: gradually progressive visual field loss
- Claused-angle glaucoma: sudden ocular pain, halos around lights, red eye, very high intraocular pressure, nausea and vomiting, suddenly decreased vision, and a fixed, mid-dilated pupil.
- Untreated glaucoma can progress to total vision loss.
- Once lost, vision cannot normally be recovered, treatment is preventing further loss. If the condition is detected early, it is possible to hinder or slow the progression with medical and surgical means.

Causes: ocular hypertension, ethnicity (higher risk for East Asian descendants), three times more risk for women than men, various rare congenital or genetic eye malformations, family history, age (the loss of vision often occurs gradually over a long period of time, and symptoms only occur when the disease is quite advanced, 1/10 of people over 80 are affected).

Propagation: Glaucoma is the second-leading cause of blindness worldwide after cataracts.

VII.2.4 Iritis

Definition: Inflammation of the iris. "Acute iritis": heals within a few weeks and improves quickly when treated. "Chronic iritis": exists for months or years before recovery, does not respond to treatment as well as acute iritis, higher risk of serious visual impairment.

Symptoms:

- Ocular pain
- Pain in affected eye when light shines in unaffected eye
- Blurred or cloudy vision
- Reddened eye, especially adjacent to the iris
- White blood cells seen as tiny white dots and protein resulting in a grey or near-white haze
- Adhesion of iris to lens or cornea
- Motion sickness

Causes: Physical eye trauma, inflammatory and autoimmune disorders (ex.: rheumatoid arthritis), infections (ex.: tuberculosis), cancer.

VII.2.5 Kjer's Optic Neuropathy

Definition: Inherited, genetic disease that affects the optic nerves, causing reduced visual acuity and blindness.

Symptoms:

- Affects both eyes roughly symmetrically
- Slowly progressive pattern of vision loss
- Areas of impaired visual acuity in the central visual fields, peripheral vision sparing
- Impaired color vision or color blindness
- Ranging from mild to severe vision loss, in rare cases vision loss is more severe.

Causes: mitochondrial dysfunction mediating the death of optic nerve fibers, inherited optic neuropathy

Propagation: most common genetic disease of the optic nerves aside from glaucoma

VII.2.6 Macular Degeneration

Definition: Loss of vision in the macula (center of the visual field) because of damage to the retina. "Dry" form: vision loss through loss of photoreceptors in the central part of the eye. "Wet" form: vision loss due to abnormal blood vessel growth.

Symptoms:

- Loss of the central vision, so that reading and recognizing faces can become difficult, although enough peripheral vision may allow other activities of daily life.
- Loss of contrast sensitivity: contours, shadows, and color vision are less bright.
- Rarely total loss of vision.

Causes: aging (>50 years), family history, different genetic conditions, hypertension, obesity, cholesterol, fat intake, exposure to sunlight and smoking.

Propagation: It is a major cause of blindness and visual impairment in older adults (>50 years). In France an estimated two million of people have this disease and the number is expected to double in the next 20 years because of the population getting older.

VII.2.7 Optic Neuritis

Definition: Inflammation of the optic nerve resulting in a complete or partial loss of vision. Swelling and destruction of the layer covering the optic nerve, or direct axonal damage.

Symptoms:

- Sudden loss of vision (partial or complete)
- Blurred or "foggy" vision
- Pain when moving the affected eye
- Blackened vision, as when feeling dizzy
- Optionally loss of color vision in the affected eye (especially red), with colors appearing washed out

Causes: multiple sclerosis, infection (e.g. syphilis, Lyme disease, herpes zoster), autoimmune disorders (e.g. lupus), inflammatory bowel disease, drugs, diabetes, gender (higher risk for females), typically affects young adults ranging from 18–45 years of age.

VII.2.8 Retinal Detachment

Definition: Retina peels away from its underlying layer of support tissue. Initial detachment may be localized, but without treatment results in detachment of the entire retina, leading to vision loss and blindness. Different types exist.

Symptoms:

- Dense shadow that starts in the peripheral vision and slowly progresses towards the central vision
- Impression that a curtain was drawn over the field of vision
- Straight lines suddenly appear curved
- Central visual loss
- Potentially total loss of vision

Commonly preceded by a posterior detachment with these symptoms:

- Brief flashes of light in the extreme peripheral part of vision
- Sudden dramatic increase in the number of floaters, ring of floaters or hairs to the temporal side of the central vision
- Slight feeling of heaviness in the eye

Causes: break in the retina that allows fluid to pass; inflammation, injury or vascular abnormalities that results in fluid accumulating underneath the retina without the presence of a hole, tear, or break; tumor on the layers of tissue beneath the retina; injury, inflammation or neovascularization that pulls the sensory retina from the retinal pigment epithelium; trauma; more common in people with severe myopia; more frequent after surgery for cataracts; proliferative diabetic retinopathy; 15% chance of it developing in the second eye.

Propagation: Around 5 new cases in 100,000 persons per year. More frequent in middle-aged or elderly populations, with rates of around 20 in 100,000 per year. The lifetime risk in normal individuals is about 1 in 300.

VII.2.9 Retinitis Pigmentosa

Definition: Inherited, degenerative eye disease resulting in severe vision impairment and blindness. Caused by abnormalities of the photoreceptors (rods and cones) or the pigmented layer of the retina.

Symptoms:

- Progressive vision loss
- Defective light to dark, dark to light adaptation or night blindness
- Tunnel vision
- Central vision may be lost first so that the person looks sideways at objects
- Ends in aversion to glare, blurring of vision, poor color separation and extreme tiredness
- People with RP can possibly see large or bright objects that are hold in their visual field long enough
- People with RP "do not look blind"

Causes: Inherited retinal degeneration, gene mutation; may be experienced early or later in life (the later the onset, the more rapid is the deterioration). Currently no treatment but the progression can be reduced.

VII.2.10 Retinoblastoma

Definition: Rapidly developing cancer in the cells of retina, the light-detecting tissue of the eye

Symptoms:

- Abnormal appearance of the pupil
- Vision loss
- Red and irritated eye with glaucoma
- Faltering growth or delayed development
- Potentionally strabismus
- In about two thirds of cases, only one eye is affected (unilateral retinoblastoma)

Causes: heritable form (mutation on chromosome 13) and non-heritable form exist; most children are diagnosed before the age of five years old.

Propagation: Rare (approximately 1 in 15,000 live births), but it is the most common inherited childhood tumor. In the developed world, it has one of the best cure rates of all childhood cancers (95-98%).

VII.2.11 Retinopathy of Prematurity / Retrolental Fibroplasia

Definition: Eye disease that affects prematurely-born babies.

Symptoms:

- Scarring and retinal detachment
- May be mild and may resolve spontaneously, but may lead to blindness in serious cases
- Greater risk for strabismus, glaucoma, cataracts and myopia later in life

Causes: in preterm infants, the retina is often not fully vascularized, ROP occurs when the development of the retinal vasculature is arrested and then proceeds abnormally. Very low birth weight is an additional risk factor. Oxygen toxicity and relative hypoxia can contribute to the development of ROP. Supplemental oxygen exposure is a risk factor.

VII.3 Defining Devices, Modalities and Interaction

VII.3.1 Device

Users and systems both perform actions on physical devices, either to acquire or to deliver information (Nigay & Coutaz, 1997). Devices should be clearly distinguished from modalities, as information presentation is not dependent on how modalities map onto devices (Bernsen, 1995). For instance similar functionality can be achieved with a mouse or other pointing devices.

VII.3.2 Input and Output Interaction

There is a distinction between input and output interaction. The user produces input modalities to the system and the system produces output modalities to the user (Bernsen, 2008). Nigay & Coutaz (Nigay & Coutaz, 1997) proposed a pipe-line model for describing the relation of input and output interaction. In this model, users have mental representations and intentions which influence how they interact with a physical input device. The user input is translated into interaction languages which then result in actions in the functional core of the systems. The results of these actions are translated into interaction languages which are then presented to the users through a physical device. This presentation again influences the users' mental representation and intentions. The model foresees shortcuts between physical input and output devices, as well as input and output interaction languages. This makes sense, as input and output are closely linked. For instance a system may provide feedback directly after input from the user has occurred (Dragicevic, 2004). In principle there should be as many input as output modalities. However, several examples of input modalities do not have equivalents in the output domain (Bernsen, 1995). For instance, gestural input interaction is becoming more and more common, whereas gestural output from machines to humans is rare (except in the domain of robotics). According to Bernsen (2008) there are three reasons for this asymmetry between input and output. First, computers have more input modalities at their disposal than human beings. For instance, humans cannot perceive X-ray whereas computers can. Second, the thresholds for perceiving information in some modalities are less restrictive for computers than for humans. Third, computers can output information that humans are in-capable of perceiving, for instance sound outside the perceivable frequencies.

VII.3.3 Interaction Technique

An interaction technique is a way of using a physical device to perform a task in a human-computer interaction (Foley et al., 1996). More precisely, interaction techniques are defined by the combination of a physical device and an interaction language (Nigay &

Coutaz, 1997). Interaction languages are languages employed by the user or the system to exchange information. Buxton (2007) proposed a contrasting view. He claimed that interaction techniques could be the same independent of the device that was used (for instance pointing with a mouse or pointing with a touchscreen). Flexibility and robustness are important characteristics of interaction techniques (Nigay & Coutaz, 1997). Interaction flexibility denotes the multiplicity of ways with which the user and the system exchange information. Interaction robustness relates to the successful achievement of goals.

VII.3.4 Modality

The definition of modality in human-interaction is not strictly equivalent to the definition of human sensory modality (Bernsen, 1995). Bernsen (2008) defined modalities as way of representing information in some physical medium. A physical medium is light for vision, sound waves for audition and mechanical contact for touch. Consequently, a modality is defined by its physical medium and its particular "way" of representation. Text, graphics and gestures are all perceived by vision and transported by the physical medium of light. However, the way of presenting information is different and thus is the modality. Bernsen (2008) mentioned different aspects that influence the choice of modalities. First, modalities differ in expressiveness, i.e. modalities are adapted for transporting different types of information. As an example it may be easier to understand spatial relations from a map than from verbal descriptions. Second, the purpose is important. For instance, verbal description might be sufficient to convey general information regarding an environment. However, if one wants to travel to a place, he might want to look at a map beforehand. Third, the abilities and skills of the user, for instance regarding perception and cognition, also influence the modalities to be used. For instance, information must be presented in a non-visual modality to visually impaired people, but also to sighted people in specific situations. For designers it is easier to develop accessible applications if more modalities are available (Bernsen, 2008).

Bernsen (1995) proposed a taxonomy of input and output modalities for task-oriented human-machine interaction. This taxonomy was based on the media of graphics (including text), acoustics and kinesthetic. Only recently and only few technical systems so far make use of olfaction and the sense of taste (for an example see Nakamura & Miyashita, 2012). While at long-term the taxonomy will probably need extension to the media of smell and taste, for the concrete application of interactive maps, it makes sense to investigate only vision, audition and touch. Bernsen (1995) further distinguished linguistic and non-linguistic, analogue or non-analogue, arbitrary or non-arbitrary, static or dynamic modalities. Linguistic modalities are for instance speech and text, whereas graphics are non-linguistic. Analogue modalities possess a similarity between the representation and what is being represented (Bernsen, 2008). For instance the drawing of an object is analogue as it resembles the original object (obviously this is not valid for some modern art forms). The names for an object vary in different languages and are non-analogue. Arbitrary modalities get their meaning assigned when they are introduced (Bernsen, 2008). For instance the use of a certain texture for representing water in a tactile map is arbitrary as there is no fixed convention. The use of the braille alphabet is non-arbitrary as each letter of the alphabet is clearly defined. Arbitrary modalities introduce a cognitive charge for learning which increases with the number of arbitrary items to be learnt (Bernsen, 2008). Finally, static representations do not mean that the representations are physically fixed but that the user can inspect them for as long as wanted. Typically this concerns the difference between graphic and acoustic modalities as we have discussed before (see II.1.3). Static graphic modalities, for instance written text, allow the simultaneous representation of large amounts of information for as much time as necessary. In contrast, dynamic output modalities such as speech are sequential and fugacious and do not offer the freedom of perceptual inspection for as much time as wanted. If the auditory output is repeated as long as the user needs for inspection it becomes static.

VII.3.5 Mode

The term "mode" has a linguistic similarity to "modality", but they denominate different things. A mode is a system state at a given time (Bellik, 1995). In this state only a subset of all existing interactions can be performed (Foley et al., 1996).

VII.3.6 Multimedia

There is a distinction between multimodal and multimedia systems. Coutaz and Caelen (1991) defined multimedia systems as computer systems which are able to acquire, store and deliver multimedia information. In comparison with multimodal systems they do not interpret the information they handle. In contrast, a computer system is said multimodal if it is able to support human-computer interaction by modalities such as gesture, written or spoken language with the competence of a human interlocutor (Coutaz & Caelen, 1991). It must be able to acquire and render multimodal expressions in real time. It must be able to choose the appropriate output modalities and produce meaningful output expressions, as well as to understand multimodal input expressions.

VII.3.7 Multimodality

Multimodal interaction has been introduced by Bolt (1980) with the "put-that-there" system. This prototype made use of combined gestural and speech input in order to draw, move and modify geometric forms on a visual display. According to Bernsen

(2008) a unimodal interactive system is a system which uses the same single modality for input and output (for instance audio input and output). In contrast, a multimodal interactive system uses at least two different modalities for input and/or output. There are various possibilities for combining input and output modalities and therefore the number of possible multimodal systems is larger than the number of possible unimodal systems (Bernsen, 2008).

Coutaz and Caelen (1991) proposed to classify multimodal systems in exclusive multimodal and synergic multimodal systems. Exclusive multimodal systems propose several modalities to the user but only one modality can be used as input (or output). The interaction is sequential. Synergic multimodal systems propose multiple modalities and the user makes combined and parallel use of the modalities for input (or output) interaction. Bellik (1995) extended this classification of interactive systems with regard to the three dimensions: one or several modalities used to form an interaction expression, parallel or sequential building of an interaction expression, and exclusive or simultaneous interaction. This results in several system types. First, exclusive multimodality is based on sequential expressions and each expression is built up by one single modality. Second, alternating multimodality is built of sequential expressions with alternating modalities. Third, synergic multimodality is based on several modalities for each expression that are used in parallel. Fourth, parallel exclusive multimodality means that independent expressions can be created in parallel. However each expression is built of one concrete modality. At a concrete point in time only one modality can be active. In contrast, parallel simultaneous multimodality allows more than modality to be used at one time. Furthermore, alternating parallel multimodality in contrast means that several modalities can be used in one expression but at a concrete moment in time only one modality can be active. Finally, parallel synergic multimodality means that several expressions can be created in parallel, and within the expressions several modalities can be used at the same time.

Nigay & Coutaz (1997) defined the system CARE properties (complementary, assignment, redundancy and equivalence) to describe the relationship between devices and interaction languages, as well as the relationship between interaction languages and tasks. Interaction languages are equivalent, if tasks can be expressed using either one of the languages. They are assigned to a task if no equivalent interaction language exists. They are complementary if a task can be partitioned so that for each partition there exists one interaction language assigned to it. Finally, interaction languages are redundant if they are equivalent and can be used simultaneously to express a task. The same is valid for the relationship between devices and interaction languages. For instance assignment connects a device to a particular language. The CARE properties can be permanent, i.e. valid for all system states, or transient. They can be total, i.e. include all tasks, or be partial. These different properties have different effects on flexibility and robustness of a system (Nigay & Coutaz, 1997). Assignment is restrictive, whereas equivalence increases flexibility as the user has the choice between different interaction languages respectively devices. Similarly, redundancy enhances flexibility and robustness. As stated by Bernsen (2008) it can be particularly useful to represent important information with redundant interaction languages respectively devices. Complementary on the other hand, increases the risk of cognitive overload.

VII.4 Tactile Maps

VII.4.1 Production

Many methods exist for producing tactile maps and images. Edman (1992) presents an exhaustive overview of possible production techniques. Raised-line drawing boards allow visually impaired people to draw their own map. For instance, the board can be made of a rubbery material. Drawing with a ball-pen over a plastic sheet placed on top of the drawing board then leaves a tactually perceivable trace in the plastic sheet. Picture types such as tactile experience pictures, buildup displays (either paper-on-paper or including additional material), paper and tape maps and charts, or displays with movable parts require costly manual preparation. Nyloprint is a technique that uses photography to engrave information on nylon or metal plates. It is based on the principle that gelatin which is applied on the plate changes its structure when exposed to light. Silk screening uses a metal or plastic stencil. Color is applied to the parts of the image that are cutout in the stencil. Variants of this technique exist such as foam ink, a special ink that expands when heated. Most recently, 3D printing has been used for the production of tactile books for blind children[61]. To our knowledge, 3D printing has not yet been used for producing tactile maps, but it might present new possibilities. Furthermore a braille embosser can be used for the creation of tactile maps. A braille embosser puts holes in the size of a braille dot into a sheet of paper. The advantage is the clear readability for braille labels produced with this method. On the contrary, the resolution is limited as an image is composed by structured holes in the paper. Besides, a sighted mobility trainer or assistant is not easily able to read the image (Wang et al., 2009). Furthermore, this method demands the acquisition of a braille embosser which comes at high cost. Vacuum-forming and swell-paper as the most common techniques are explained in the main text (II.3.3.1).

VII.4.2 Map Design

VII.4.2.1 Attempts for Standardization

There have been attempts for standardization of tactile map design. The Nottingham Map Making Kit was a first standardized map making kit for orientation and mobility symbols for visually impaired people. It has been developed in the early 70s by J.D. Armstrong and G.A. James. It was followed in 1989 by the Euro-Town Kit authored by the German Institute for the Blind (Deutsche Blindenstudienanstalt, Marburg, Germany). The Euro-Town Kit has been used in the European Union. However, as it was very expensive, it never reached wide-spread use (Lobben & Lawrence, 2012). Recently,

[61] http://www.tactilepicturebooks.org/books.html [last accessed August 27th 2013]

Picard (2012) obtained a patent for the design and production of a visuo-tactile atlas. The atlas combines visual and tactile views, so that it is accessible for blind people, visually impaired people with residual vision and sighted people, such as mobility trainers. The tactile images are created with respect to the perceptual constraints of haptic exploration. In a second step, the visual view is then created based on the tactile view, thus placing the importance on the tactile presentation. In a recent study, Lobben and Lawrence (2012) proposed a standardization of map symbols for tactile maps produced on microcapsule paper. They defined a set of tactile symbols that have proved discriminable in user studies. In this set the most important map elements (streets and intersections) were attributed the most discriminable symbols. This symbol set, released by the Braille authority of North America, has been made freely accessible on the internet and presented in workshops. As a downside it has to be noted that the set has only been tested in North American cities and it is not clear whether the same symbols can be used in European cities that tend to be less rectangular.

VII.4.2.2 Choice of the Symbol Set

VII.4.2.2.a Lines

According to Bris (1999) lines represent either linear concrete objects—like roads—or contours of two-dimensional objects. To differentiate objects, lines should have varying characteristics (such as pattern or width). Bris suggests that very specific patterns can be used to identify distinct map elements. However, more than three to five different patterns increase the risk of overloading the map reader with too much information.

In practice, Picard and Bris both proposed 8 mm as the minimum length for lines to be perceived as such, whereas Tatham (1991) proposed 13 mm. According to Bris the minimum line width (or thickness) is 0.4 mm. Tatham defined it as 1 mm and the maximum as 7 mm. Bris proposed 0.4mm also as minimum line height, however this depends on the production method and cannot always be controlled. In order to facilitate differentiation between different lines, Tatham suggested that line widths should vary at least around 25%. Bris even suggested a factor of 2 for different line widths.

For fragmented lines, another relevant variable exists: the spacing of the elements. According to Bris the spacing can be between 0.5 mm minimum and 4 mm maximum so that the elements are perceived as one line. Similar values are proposed by Tatham. It is also possible to vary the length of the dash, which should be at least as long as the spacing. According to Tatham single lines are easier to perceive than double lines. Picard suggested spacing double lines at a distance of 2mm. To avoid confusion with double lines, Tatham proposed that adjacent but separate lines should be spaced at least by 6mm. Tatham also suggested that solid lines are easier to perceive than recessed lines (which anyway is only possible with certain production methods). Finally it has to be noted that due to the specificities of kinesthetic and proprioceptive perceptions, changes of direction should be superior to 60°.

VII.4.2.2.b Textures

Textures can be useful to represent a particular space (Lederman & Kinch, 1979). The texture is the combination of the two components (Bris, 1999): first, the form (outline) of the element that is filled with the texture; second, the pattern of the texture.

Several studies have investigated the choice of textures that are easily distinguishable (Lederman & Kinch, 1979). Possible textures contain dots, lines (vertical, horizontal, diagonal or crossing lines), curves, zigzag, chessboard patterns and combinations of these in different width and size. Criteria for differentiating textures are continuity or interruption, regularity, the density of patterns and the size of elements that form the pattern. Bris underlined that the spacing of the pattern elements is important. If spacing is too wide, the feeling of texture disappears. If spacing is too dense, it is possible that the texture is perceived as one closed surface. Lederman and Kinch criticized that the choice of patterns used in tactile diagrams often seems to be made randomly. It also has to be noted that sighted map designers tend to use representations that content visual conventions, for instance wavy forms for representing water, even though these conventions are not necessarily known to visually impaired map readers.

Tatham proposed that surfaces represented by textures should be at least 12 mm in length and width so that the pattern is perceived as such and not as several adjacent lines or dots. Texture may interfere with the perception of lines and point symbols (Lederman & Kinch, 1979). If a point or line is included within a texture there should be a spacing of at least 2mm to 3 mm around the point or line so that it can be perceived separately from the texture (Bris, 1999; Tatham, 1991). Contrast is important for distinguishing adjacent textures.

VII.4.2.2.c Symbols

Single landmarks can be represented through specific symbols (Lederman & Kinch, 1979). The number of forms that are indistinguishable using the sense of touch is limited. Often points, rectangles, triangles and radiant symbols are used (Tatham, 1991). The number of possible elements can be increased by using open and solid symbols. Depending on the technique used for the map production (see II.3.3.1.b) it may be possible to add height as a third dimension to improve contrast. Edman showed a list of different symbols that have been used in maps. Lobben and Lawrence (2012) proposed a set of symbols including circles, triangles, rectangles and radiant symbols that are either open, solid or filled with lines or crosses. According to Tatham, solid symbols should be between 3 and 10 mm in size. Open and radiant symbols should be between 4 and 10 mm in size.

VII.5 Classification of Interactive Maps for Visually Impaired People

VII.5.1 Terminology

Due to the current lack of overview on existing map projects there is no standardization regarding terminology. Various names have been chosen in different publications and there is rarely an explanation or definition. Several authors used the term "audio-tactile maps" (Jacobson, 1998a; Miele et al., 2006; Paladugu et al., 2010; Parente & Bishop, 2003; Wang et al., 2009). In general—but not in all cases—this term refers to maps that are based on touch input. More specifically, these maps are mostly based on raised-line maps augmented with audio output. Zeng and Weber (2011) named this map type "augmented paper-based tactile maps". Another term that has been used is "virtual tactile maps". Schneider and Strothotte (1999) defined virtual tactile maps as digital maps that emit speech and sound when they are explored by hand movements. Their prototype consisted in a tactile grid that could be manually explored by the user and that was augmented with audio output. In contrast, Zeng and Weber (2011) used this name when referring to maps based on the use of haptic devices such as force feedback mice and auditory output. Thus, there seems to be no common consent on use of this term. Some authors referred to prototypes based on haptic devices and audio output as "haptic soundscapes" (Golledge et al., 2005; Lawrence et al., 2009; Rice et al., 2005). Lohmann and Habel (2012) proposed the name VAVETaM (verbally assisting virtual-environment tactile maps) for a similar prototype based on a haptic device and audio output. Finally, Zeng and Weber (2011) proposed "virtual acoustic maps" for maps with audio output alone and "braille tactile maps" for maps based on the use of raised-pin displays. However, the latter is surprising as raised-pin displays are not necessarily destined for braille text and also they are usually accompanied by audio output.

In this thesis we refer to "interactive maps for visually impaired people". We define that this term includes all variants of prototypes that represent geospatial information from an allocentric perspective and that are destined for visually impaired people, regardless of the devices or interaction techniques used in the map. We suggest that the name "audio-tactile maps" could be used for raised-line maps augmented with audio output as it already seems to be commonly used. Similarly, "haptic soundscapes" seems to be an accepted terminology for maps based on haptic devices and audio output. We agree on the use of "virtual acoustic maps" for maps with audio output alone. For the maps based on raised-line displays, we propose the term "dynamic tactile-audio maps", as the advantage of the raised-pin displays lies in the dynamic transformation of the tactile information.

VII.5.2 Origin of the Projects

Figure VII.1: Cities in which projects of interactive maps for visually impaired people have been developed. The figure has been produced with Gephi GeoLayout (Bastian et al., 2009) and OpenStreetMap.

Figure VII.1 shows a map of the cities in which projects of interactive maps for visually impaired people have been developed. Note that in some cases there are several universities in one city. For instance, UMBC (University of Maryland Baltimore County), the University of Maryland and Towson University are all situated in or close to Baltimore, Maryland. In some cases map projects are collaborations between several universities. In that case all cities have been reported. The map indicates that various universities have been involved in the development of accessible maps, mainly in Europe and North America.

VII.5.3 Timeline

We also analyzed the projects regarding the year of publication. Figure VII.2 shows that most projects have emerged in the past ten years.

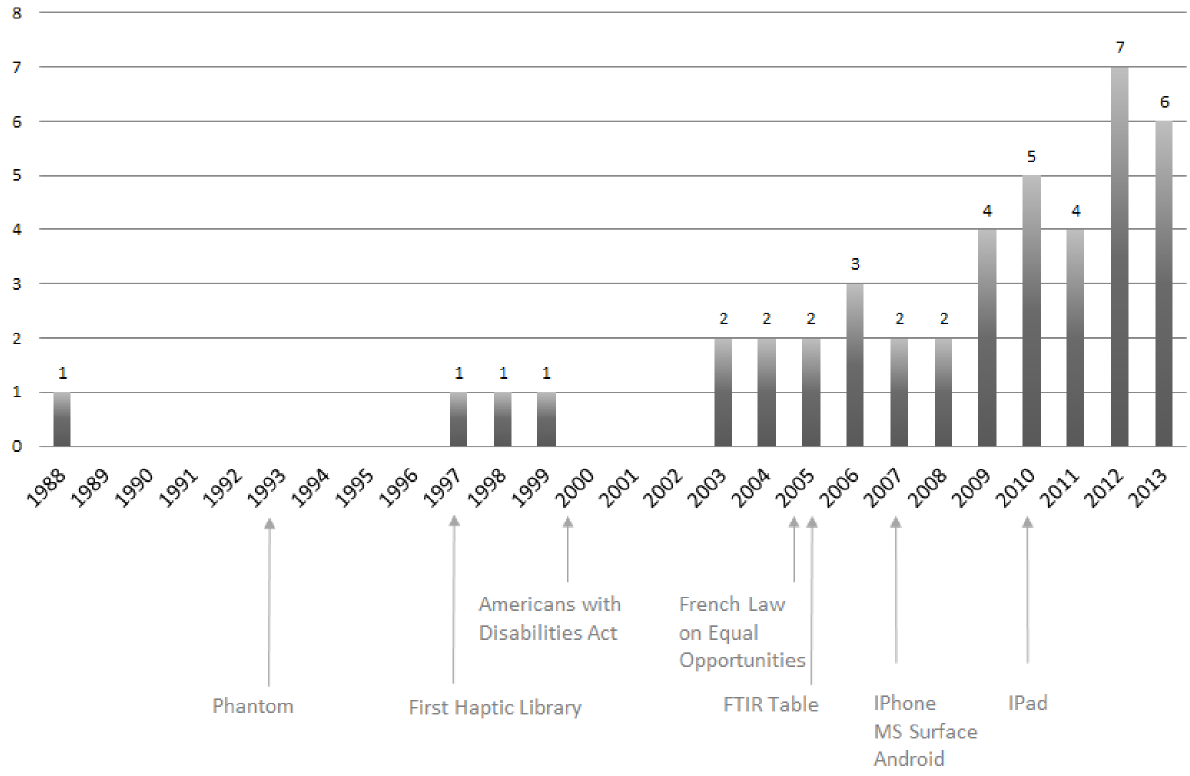


Figure VII.2: Timeline of publications on interactive maps for visually impaired people.

There might be different reasons for this recent increase. First, this might simply be related to technological progress. In the first publication on interactive maps for visually impaired people, Parkes (1988) proposed a map based on a touchscreen. However, the interest for touchscreens has risen only recently (Schöning et al., 2008). A first peak could be observed after Jeff Han's presentation of a Frustrated Total Internal Reflection Table in 2005 (Han, 2005), followed by the arrival of the IPhone, Microsoft Surface and Android in 2007. The first IPad was introduced to market in 2010. Indeed, Schneider and Strothotte (1999) stated that at the time of the development of their prototype, there were no tactile displays or touch tablets available which met all of their requirements. With the number of devices increasing, prices have decreased. A similar development has been observed in the field of haptics (Roberts & Paneels, 2007). The first Phantom device was presented in 1993 and the first haptic library (GHOST) in 1997. Roberts & Paneels consequently observed an exponential growth of scientific publications in the field of haptics since the '90s. Another reason might be that due to different laws and regulations (*Americans with Disabilities Act of 1990, Pub. L. No. 101-336, 104 Stat. 328*, 1990, *LOI n° 2005-102 du 11 février 2005 pour l'égalité des droits et des* *chances, la participation et la citoyenneté des personnes handicapées, JORF n°36 du 12 février 2005*, 2005) the interest in providing technical solutions for improving accessibility has increased. Finally, it is also possible that earlier publications have not been digitized and have therefore been forgotten. In any case, the increasing interest in accessibility is promising for improving the access to technology as well as mobility and orientation for visually impaired people.

VII.5.4 Map Content and Scale

Theoretically, most prototypes allow the representation of varying types of map content (e.g., indoor or outdoor maps) as well as map content at different scales (e.g. world map, city center). Here, we only mention the type of map content that has been reported in the corresponding publication. Figure VII.3 shows the number of publications per content. We separated Indoor Maps, Outdoor Maps and other maps (non-geographic or unknown content). Then we further distinguished content and scale within these categories.

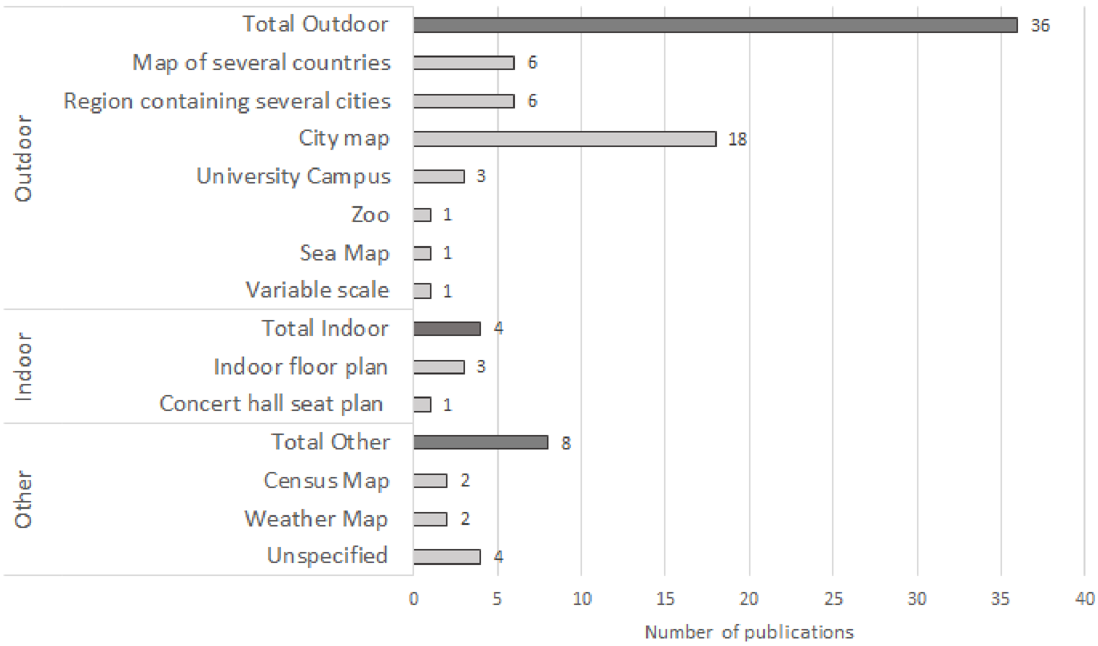


Figure VII.3: Number of publications on interactive maps for visually impaired people classified by map content and scale. Categories are presented on the left (Outdoor, Indoor and Others). The x-axis represents the number of publications. Bars in dark grey present the total for each category.

Within Outdoor Maps we noticed different scales. The largest maps represent several countries—maps depicting several states in the US have been counted in this category (Kane, Frey, et al., 2013; Kane, Morris, et al., 2011; Krueger & Gilden, 1997; Petit et al., 2008; Seisenbacher et al., 2005; Tixier et al., 2013). These maps typically show the outline of borders, major cities and eventually the border of continents and oceans. Maps of regions with several cities show similar content but sometimes contain information about road networks and water lines (De Felice et al., 2007; Jansson et al., 2006; Parente & Bishop, 2003; Rice et al., 2005; Simonnet et al., 2012; Tornil & Baptiste-Jessel, 2004). City maps depict streets and buildings, sometimes including green areas, rivers and specific information for visually impaired travelers (Brock, Truillet, et al., 2012; Campin et al., 2003; Hamid & Edwards, 2013; Heuten et al., 2007; Iglesias et al., 2004; Kaklanis et al., 2011, 2013; Lohmann & Habel, 2012; Miele et al., 2006; Milne et al., 2011; Pielot et al., 2007; Poppinga et al., 2011; Schmitz & Ertl, 2010; Senette et al., 2013; Tixier et al., 2013; Wang et al., 2009; Yatani et al., 2012). Specific forms of city maps depict a university campus (Lawrence et al., 2009; Rice et al., 2005; Zeng & Weber, 2010) or a zoo (Jacobson, 1998a). One project aimed at maritime maps for blind sailors (Simonnet et al., 2009). Finally, one project is operable at different scales (Bahram, 2013).

Indoor Maps mostly depict floor plans of buildings (Schmitz & Ertl, 2012; Su et al., 2010; Yairi et al., 2008). An exception is the seat plan of a concert hall (Lévesque et al., 2012).

The category "other" contains choropleth maps, i.e. specific thematic maps which do not serve for orientation and mobility but for transporting societal or political information in relation to a geographic area. Concretely, these are census maps (Rice et al., 2005; Zhao et al., 2008) or maps presenting weather information (Carroll et al., 2013; Weir et al., 2012). Finally, several publications did not specify the kind of content that is depicted on the map (Daunys & Lauruska, 2009; Parkes, 1988; Schneider & Strothotte, 1999; Shimada et al., 2010).

As can be seen in Figure VII.3, outdoor maps are more common than other map types. Within outdoor maps, the most common are city maps. This makes sense as these maps directly respond to the need of visually impaired people to improve mobility and orientation. In comparison, maps that depict regions or countries are rather used for teaching geography. Orientation inside buildings is certainly also important for visually impaired people. We propose two reasons why these types of maps are less common. First, even if the problems of constructing mental maps are comparable for indoor and outdoor maps, navigation itself is more problematic - and dangerous - in outdoor areas. Therefore, visually impaired people might potentially experience more fear related to outdoor mobility. Second, there is more information available on outdoor areas and thus the design of the physical map can be based on existing data. Google Maps is currently working on indoor floor plans[62]. Due to the increasing availability of information on indoor settings, possibly in the near future more accessible indoor maps might be available.

VII.5.5 Non-Research Projects

Our classification included only research projects. Yet, other projects have been developed outside academia.

One of the earliest projects we heard about was ABAplans[63]. ABAplans was originally a research project of the Engineering School of Geneva (Ecole d'ingénieurs de Genève). Its aim was to allow users to navigate the map of a city, find a place, prepare trips and learn about public transportation. Two approaches have been developed. First, a map editor destined for locomotion instructors. Second, an interactive device based on a raised-line map as overlay on a mono-touch screen. Users could explore the relief map and receive audio output for certain map elements. ABAplans is currently in the phase of commercialization.

The company ViewPlus offers the IVEO system[64]. It consists of a monotouch screen adapted for use with raised-line maps. It comes with software for the drawing of raised-line maps and drawings. Optionally it is possible to purchase software that allows creating raised-line images from PDF or scanned documents using optical character recognition technology. The user must possess the equipment to print the relief maps. For this purpose ViewPlus also offers braille embossers.

Earth+[65] was a project developed by the NASA with the aim to develop accessible map representations. In contrast to other projects that provide speech output, Earth+ provided musical sound output depending on the colors in the image. The user interacted with the system by moving a mouse cursor in the image. The tool remained in beta version and has not been further developed since 2009.

Ariadne GPS[66] is a commercial map application for Ipad or IPhone that is under ongoing development. It has been developed for these devices as many blind people already use them because of the good screen reader qualities. It resembles in its

62 http://maps.google.com/help/maps/indoormaps/ [last accessed August 21st 2013]

63 http://abaplans.eig.ch/index.html [last accessed June 10th 2013]

64 http://www.viewplus.com/products/software/hands-on-learning/ [last accessed September 11th 2013]

65 http://prime.jsc.nasa.gov/earthplus/ [last accessed August 22nd 2013]

66 http://www.ariadnegps.eu/ [last accessed August 22nd 2013]

concepts the TouchOverMap (Poppinga et al., 2011). The user can move the finger on the touchscreen and receives audio and vibrational feedback through the use of the VoiceOver[67] screen reader. Besides map exploration, Ariadne GPS also takes into account mobile information, for instance by alerting users when they approach favorite points.

Figure VII.4: The iDact prototype provides accessible information about metro stations in Paris. Reprinted with permission.

IDact[68] is another application for iPad (see Figure VII.4). Its objective is to provide accessible maps for train and metro stations. Information is provided by speech output. The iDact project is currently under development.

[67] http://www.apple.com/accessibility/osx/voiceover/ [last accessed August 22nd 2013]

[68] http://www.idact.eu/ [last accessed August 22nd 2013]

VII.6 Interactive Map Prototype

VII.6.1 Ivy Communication Protocol

VII.6.1.1 Message emitted by the touch detection module

Each new touch input leads to a new message of the following type:

CIM TestPoint idFinger=AAA x=XXX y=YYY precision=PPP t=TTT

- CIM TestPoint : Message Identifier
- idFinger: identifier of the touch input (with the Stantum touchscreen each new touch input automatically creates a new id, with the 3M screen IDs are reused)
- x and y: coordinates x and y in pixel related to the superior left point of the screen.
- precision: defines the precision of the touch. As the hardware does not give any precision information, the value 1 has been set as default
- t: timestamp in milliseconds

The following message indicates the state for each touch input:

MTM Cursor idFinger=AAA State=EEE

- MTM Cursor: message identifier
- idFinger: identifier of the touch input
- State: either « created », « down », « move » or « up » (this state is created by the touch hardware)

Finally, the following message indicates the alive state of the device

MTM Device State=alive Cursors=CCC Sequence=TTT

- MTM Device State=alive: Messager identifier
- *Cursors*: number of current touch inputs
- *Sequence:* timestamp in milliseconds, identic to the timestamp used in the messages TestPoint and ResPoint

VII.6.1.2 Message emitted by the viewer module

The viewer module uses the coordinates from the "CIM TestPoint" message to do a picking in the SVG image and determine the touched element. It then sends the following message:

CIM ResPoint idFinger=AAA idObject=III t=TTT

- CIM ResPoint: Message Identifier
- idFinger: identifier of the touch input (with the Stantum touchscreen each new touch input automatically creates a new id)
- idObject: identifier of the object in the SVG file
- t: timestamp in milliseconds

VII.6.1.3 Message emitted by the interactive map module

The messages "CIM TestPoint" and "CIM ResPoint" (described above) are used by the interactive map module to handle the state machine. After determining that an interactive element has been activated, it sends a message to the TTS module:

TTS Say=SSS

- TTS : message identifier
- Say : String for speech output

VII.6.2 Lexical Map Content

VII.6.2.1 Street Names

Description of the wording of street names in map 1 (a) and map 2 (b). Code is the abbreviation used on the braille map for the French wording. Each map contains two terms for each category flowers, precious stones and birds. Each term is a two-syllable word (= bi). All words are low-frequency terms (= LF).

Table VII.1: Wording of street names in map 1 (a) and map 2 (b). Each map contains two terms for each category flowers, precious stones and birds. Each term is a two-syllable word (= bi). All words are low-frequency terms (= LF).

a.

Code	French	English	Category	Frequency	Syllables	Classification
rg	gentiane	gentian	flower	0,14	2	LF bi
rs	saphir	sapphire	precious stone	0,34	2	LF bi
rl	linotte	linnet	bird	0,69	2	LF bi
rj	jasmin	jasmine	flower	1,57	2	LF bi
rr	rubis	ruby	precious stone	2,22	2	LF bi
rp	pinson	chaffinch	bird	2,68	2	LF bi

b.

Code	French	English	Category	Frequency	Syllables	Classification
rg	glycine	wisteria	flower	0,21	2	LF bi
rt	topaze	topaz	precious stone	0,36	2	LF bi
rp	puffin	shearwater	bird	0,54	2	LF bi
rl	lavande	lavender	flower	1,53	2	LF bi
rd	diamant	diamond	precious stone	7,97	2	LF bi
rb	bécasse	woodcock	bird	1,4	2	LF bi

VII.6.2.2 Points of Interest

Description of the wording of POI in map 1 (a) and map 2 (b). Code is the abbreviation used on the braille map for the French wording. Each map contains three words with low frequency (= LF) and three words with high frequency (=HF). For each of the two frequency one word has one syllable (= mono), one has two syllables (= bi) and one has three syllables (= tri).

Table VII.2: Description of the wording of POI in map 1 (a) and map 2 (b). Each map contains three words with low frequency (= LF) and three words with high frequency (=HF). For each of the two frequency one word has one syllable (= mono), one has two syllables (= bi) and one has three syllables (= tri).

Code	French	English	Frequency	Syllables	Classification
o	obélisque	obelisk	0,1	3	LF tri
h	halles	halls	0,57	1	LF mono
m	métro	metro	17,66	2	LF bi
p	parc	park	31,02	1	HF mono
é	église	church	60,2	2	HF bi
c	cinéma	cinema	62,23	3	HF tri
hô	hôtel	hotel	107,73	2	HF bi

a.

Code	French	English	Frequency	Syllables	Classification
h	hippodrome	racecourse	0,52	3	LF tri
s	spa	spa	0,79	1	LF mono
m	musée	museum	18,59	2	LF bi
g	gare	railway station	40,28	1	HF mono
r	restaurant	restaurant	44,29	3	HF tri
j	jardin	public garden	54,01	2	HF bi
hô	hôtel	hotel	107,73	2	HF bi

b.

VII.6.3 Recommendations for Developing Interactive Maps

These recommendations apply when developing an interactive map based on a multi-touch screen, raised-line overlay and speech output.

Tactile Map Drawing

Existing guidelines on tactile map drawings have served as a basis for these recommendations (Bris, 1999; Edman, 1992; Picard, 2012; Tatham, 1991):

- Swell paper is a well-adapted, easy and low-cost production method
- Keep it simple
    - in terms of the number of elements (max. 30)
    - in terms of the number of different shapes and textures (max 8)
    - in terms of the complexity of shapes and textures
- Contrast is important (between textures, shapes, sizes, etc.)
- Proposed dimensions for lines, textures and symbols can be found in the appendix (VII.4.2.2)
- When printing on swell paper, avoid too much black paint on the image because it turns printing more difficult

Multi-touch Device

The multi-touch device must comply with several criteria:

- Compatibility with a raised-line overlay is guaranteed for resistive, projected capacitive, SMART and out of plane technology
- Multi-touch input enables more advanced gestural interaction
- Best adapted size are A3 or A4 format
- Pointing precision better than the size of a fingertip
- Horizontal orientation provides comfortable map reading position

Software Architecture

- A modular software architecture enables easy prototyping and replacing modules

- An existing gestural API provides pre-defined gestures and is more stable
- Provide at least touch input and speech output, eventually combined with further modalities and interaction techniques
- A braille display can be used as a complement to display text
- Simple taps are likely to be activated accidentally. Provide at least double tap input
- Gestural interaction can be used
- Assure a good comprehension of speech output, concerning speed, volume and the quality of the voice

Evaluation

- Always foresee pretests
- Test with visually impaired people if possible

VII.7 Participatory Design with Visually Impaired People

Summary of the recommendations as described in chapter III.

Participants

- Include specific criteria such as degree of visual impairment, the proportion of lifetime with blindness or the age at onset of blindness, autonomy in everyday life, braille reading skills or use of assistive technology.
- Low-vision and blind people do not have the same requirements. It may be useful to focus on a specific sub-group.
- Local associations can be helpful for the recruitment.
- Accessible communication tools for the recruitment process and for exchanging information include Google Sites and Doodle. Many visually impaired people use smartphones and email.
- Speakers should be orally introduced (at least at the first encounter).
- Keep fixed seating arrangements during a session.
- Limit the size of groups to ten people.
- Interviews are preferred over questionnaires.
- Give explanations in case the contact person (researcher) changes.
- Handle the participants' expectations. Unfortunately there is little chance that they are personally going to benefit from the outcome of the research.

Logistics

- Describe the outline of the room.
- Foresee space for the guide dog.
- Plan transportation in advance.

Analysis Phase

- Take time for understanding users' needs, especially when working with impaired users for the first time
- Even if existing research is useful, it is very important to actually meet and observe users

Generating Ideas

- Brainstorming can be made accessible
  - The facilitator should be in charge by making the content accessible (reading it out, structuring it).
  - The facilitator must also handle turn taking between speakers.
  - Visually impaired users can take notes with the BrailleNote device.
- Wizard of Oz simulation is a useful method for stimulating ideas for new and innovative concepts.
  - Modalities in the Wizard of Oz simulation should correspond to the interaction modalities in the final prototype./

Prototyping

- We suggest an iterative procedure with software-based low-fidelity prototypes.
- Pretests with visually impaired people along the prototyping process ensure that visually impaired people's requirements are met.

Evaluation

- Guidelines, heuristics and standards are helpful, but prototypes should be evaluated with real users.
- Tests for evaluating spatial knowledge without sight are presented in III.2.6.1.
- The SUS questionnaire is adapted for evaluating usability.

VII.8 Experimental Study (Chapter IV)

VII.8.1 Participants

Figure VII.5 Detailed characteristics of the visually impaired participants in our study.

Subject	Education level	Travel aids (in addition to white cane)	New technologies
1	university		computer, cell phone, mp3
2	university	electronic travel aid	computer, cell phone, mp3
3	university	electronic travel aid	computer, cell phone, mp3
4	university		Computer, cell phone
5	university		Computer, cell phone
6	secondary school	electronic travel aid	computer, cell phone, mp3
7	vocational education	guide dog	computer, cell phone, mp3
8	secondary school		computer, cell phone, mp3
9	higher education		computer, cell phone, mp3
10	vocational education		computer, cell phone, mp3
11	university	guide dog	computer, cell phone, mp3
12	university	electronic travel aid	computer, cell phone, mp3
13	university	guide dog	computer, cell phone, mp3
14	university		computer, cell phone, mp3
15	university		computer, cell phone, mp3
16	vocational education	electronic travel aid	computer, cell phone
17	university	guide dog	computer, cell phone, mp3
18	vocational education		computer, cell phone
19	university	electronic travel aid	computer, cell phone, mp3
20	vocational education		computer, cell phone, mp3
21	higher education		computer, cell phone
22	university	electronic travel aid	computer, cell phone, mp3
23	university		computer, cell phone
24	university	guide dog	computer, cell phone, mp3

VII.8.2 User Study Questionnaire

Niveau de scolarité *
Dernière classe fréquentée ou dernier diplôme obtenu (par exemple troisième, bac, licence...)

Profession

Activité actuelle

Etes-vous inscrit au service Mobibus de Tisséo ?

- oui
- non

Cécité

Age d'apparition de la cécité *

L'apparition de votre cécité était-elle progressive ou brutale ?

- Progressive
- Brutale

Si elle était progressive, à partir de quel âge est-elle devenue invalidante d'après vos souvenirs ?

Quelle est la cause de la cécité ?

- accidentelle
- congénitale
- maladie
- autre

Si maladie, quel type ?

Avez-vous une perception résiduelle ?
de la lumière ou des formes par exemple

- oui
- non

Cette perception résiduelle est-elle fonctionnelle ?

- oui
- non

Acuité visuelle oeil droit *
par exemple en /10° ou /20°

Acuité visuelle oeil gauche *
par exemple en /10° ou /20°

Acuité visuelle oeil droit avant la dégradation
par exemple en /10° ou /20°

Acuité visuelle oeil gauche avant la dégradation
par exemple en /10° ou /20°

Certaines personnes peuvent avoir plusieurs déficiences. Est-ce votre cas ?

- oui
- non

Si vous avez une autre déficience, comment la définiriez-vous ?

Au cours de votre vie, avez-vous eu d'autres maladies particulières, ou avez-vous eu des accidents ?
Par exemple, certaines personnes peuvent être epileptiques, avoir des atteintes cérébrales, ou des troubles du comportement.

Braille

Etes-vous lecteur braille ?

- oui
- non

si oui, depuis quel âge ?

si oui,

- une main
- deux mains séquentiels
- deux mains parallèle

Lisez-vous le braille abrégé ?

- oui
- non

A quelle fréquence utilisez-vous le braille ?
de rarement (indiquez 1) à trés souvent (indiquez 5). Moyennement (indiquez 3)

	1	2	3	4	5	
rarement	○	○	○	○	○	très souvent

Quelle est votre expertise en lecture braille ?
de peu expert (indiquez 1) à très expert (indiquez (5). Moyennement (indiquez 3)

	1	2	3	4	5	
peu expert	○	○	○	○	○	trés expert

Images tactiles

il existe plusieurs types d'images en relief que nous appelons images tactiles, par exemple : les graphiques, les dessins, les cartes. Mais il en existe d'autres que vous connaissez peut-être.

Avez-vous eu l'occasion d'utiliser des images tactiles .

- oui
- non

A quelle fréquence utilisez-vous des images tactiles ?

	1	2	3	4	5	
rarement	◯	◯	◯	◯	◯	très souvent

Quelle est votre aisance dans l'exploration et la lecture d'images tactiles ?

	1	2	3	4	5	
trés faible aisance	◯	◯	◯	◯	◯	forte aisance

Usage du sens du toucher

Dans la vie de tous les jours, lorsque vous avez le choix entre l'utilisation de plusieurs sens, diriez-vous que utilisez :
par exemple si vous utilisez un lecteur d'écran et que vous devez choisir entre la synthèse vocale et un afficheur braille, ou entre un livre audio et un livre en braille

	1	2	3	4	5	
uniquement un autre sens	◯	◯	◯	◯	◯	uniquement le toucher

Latéralité manuelle

Voici quelques questions qui vont permettre d'évaluer votre latéralité manuelle

Avec quelle main lisez-vous le braille ?

- ◯ uniquement la main gauche
- ◯ les deux
- ◯ uniquement la main droite

Avec quelle main dessinez-vous ?

- ◯ uniquement la main gauche
- ◯ les deux
- ◯ uniquement la main droite

Avec quelle main lancez-vous des objets ?

- ◯ uniquement la main gauche
- ◯ les deux
- ◯ uniquement la main droite

Avec quelle main utilisez-vous des ciseaux ?

- uniquement la main gauche
- les deux
- uniquement la main droite

Avec quelle main vous brossez-vous les dents ?

- uniquement la main gauche
- les deux
- uniquement la main droite

Avec quelle main utilisez vous un couteau ? (sans la fourchette)

- uniquement la main gauche
- les deux
- uniquement la main droite

Avec quelle main utilisez-vous une cuillere ?

- uniquement la main gauche
- les deux
- uniquement la main droite

Avec quelle main utilisez-vous un balai ? (main d'en haut)

- uniquement la main gauche
- les deux
- uniquement la main droite

Avec quelle main allumez-vous une allumette ?

- uniquement la main gauche
- les deux
- uniquement la main droite

Avec quelle main retirez-vous le couvercle d'une boite ?

- uniquement la main gauche
- les deux
- uniquement la main droite

Déplacements

Lorsque vous vous déplacez en dehors de chez vous, comment se déroulent vos déplacements ?
plusieurs réponses sont possibles

- plutot seul
- plutot accompagné
- canne blanche
- chien guide
- système d'aide electronique (par exemple kapten ou trekker)

Pour la préparation d'itinéraires, utilisez-vous ?

- GPS (exemple, kapten, trekker)
- carte tactile
- planification d'itinéraire sur internet (mappy, google maps, via michelin ou autre)
- description d'un itinéraire par une autre personne
- autre chose
- rien

Moyen de déplacement : lorsque vous devez vous rendre quelque part en dehors de chez vous, comment vous déplacez-vous ?

- à pied
- Bus-Metro-Tram
- en taxi
- en mobibus

A quelle fréquence vous déplacez-vous ?

	1	2	3	4	5	
rarement	○	○	○	○	○	tous les jours

Avez-vous confiance lors de vos déplacements ?

	1	2	3	4	5	
faiblement	○	○	○	○	○	tout à fait

Avez-vous le sens des directions, de l'orientation ?

	1	2	3	4	5	
faiblement	○	○	○	○	○	tout à fait

Nouvelles technologies

Utilisez-vous les nouvelles technologies ?

- Ordinateurs
- Baladeurs mp3
- Téléphone portable
- autres

L'usage des nouvelles technologies est-il familier pour vous ?

	1	2	3	4	5	
peu familier	○	○	○	○	○	trés familier

Quelle est votre aisance avec les nouvelles technologies ?

	1	2	3	4	5	
faible aisance	○	○	○	○	○	bonne aisance

Hobbies

Quels sont vos principaux loisirs ?
par exemple : la musique, la lecture, randonnée, internet...

Avez-vous déjà participé en tant que volontaire à des études en psychologie ?

- oui
- non

VII.8.3 Santa Barbara Sense of Direction Scale

Questionnaire based on Santa Barbara Sense of Direction Scale and translated in French

ECHELLE SANTA BARBARA DU SENS DES DIRECTIONS V. 2

Sexe: F M Date de passation :_______________

Âge :_______

Ce questionnaire se compose de plusieurs énoncés au sujet de vos expériences, vos préférences et de vos capacités spatiales et de navigation. Après chaque affirmation, vous devez choisir un chiffre pour indiquer votre niveau d'accord avec l'énoncé. Choisissez "1" si vous êtes fortement d'accord avec l'énoncé, choisissez "7" si vous n'êtes pas du tout d'accord avec l'énoncé, ou un nombre entre les deux selon votre degré d'accord. Choisissez le «4» si vous êtes ni d'accord, ni en désaccord.

1. Je sais très bien indiquer un itinéraire (ex : de chez vous au magasin).

1	2	3	4	5

Tout à fait d'accord — Pas du tout d'accord

2. J'ai une mauvaise mémoire des endroits où j'ai laissé des choses.

1	2	3	4	5

Tout à fait d'accord — Pas du tout d'accord

3. Je sais très bien évaluer les distances.

1	2	3	4	5

Tout à fait d'accord — Pas du tout d'accord

Comment procédez-vous ? (temps, distance) ______________________________

4. Mon "sens de l'orientation" est très bon.

1	2	3	4	5

Tout à fait d'accord — Pas du tout d'accord

5. J'ai tendance à penser mon environnement en termes de points cardinaux (Nord, Sud, Est, Ouest) ou horaires.

1	2	3	4	5
Tout à fait d'accord				Pas du tout d'accord

□ Points cardinaux □ horaires

6. Je prends beaucoup de temps pour me repérer dans une nouvelle ville.

1	2	3	4	5
Tout à fait d'accord				Pas du tout d'accord

7. J'aime lire des cartes.

1	2	3	4	5
Tout à fait d'accord				Pas du tout d'accord

8. J'ai du mal à comprendre les itinéraires.

1	2	3	4	5
Tout à fait d'accord				Pas du tout d'accord

9. Je sais très bien lire les cartes.

1	2	3	4	5
Tout à fait d'accord				Pas du tout d'accord

10. Je ne me souviens pas très bien des routes quand je suis accompagné.

1	2	3	4	5
Tout à fait d'accord				Pas du tout d'accord

11. Je n'aime pas décrire un itinéraire.

1	2	3	4	5
Tout à fait d'accord				Pas du tout d'accord

12. Ce n'est pas important pour moi de savoir où je suis.

1	2	3	4	5

Tout à fait d'accord — Pas du tout d'accord

13. J'ai l'habitude de laisser quelqu'un d'autre planifier le trajet.

1	2	3	4	5

Tout à fait d'accord — Pas du tout d'accord

14. Généralement je me souviens d'un nouveau trajet après l'avoir parcouru une seule fois.

1	2	3	4	5

Tout à fait d'accord — Pas du tout d'accord

15. Je n'arrive pas très bien à me représenter mon environnement.

1	2	3	4	5

Tout à fait d'accord — Pas du tout d'accord

VII.8.4 SUS questionnaire translated into French

Vous avez testé deux types de cartes, une carte papier et une carte interactive. Ces deux types de cartes ont été mises au point par des chercheurs de l'IRIT, et nous voudrions savoir quel type de carte est le plus satisfaisant pour vous en tant qu'usager. Votre avis compte et pour cela nous vous proposons le questionnaire de satisfaction suivant. Il se compose de 10 propositions ; vous devrez indiquer dans quelle mesure vous êtes d'accord avec chacune de ces propositions, en utilisant une échelle en 5 points, de 1 = pas du tout d'accord à 5 = tout à fait d'accord. Afin de connaître votre avis pour chaque type de carte, vous jugerez chaque proposition pour la carte papier et pour la carte interactive. A la fin du questionnaire, vous aurez également l'occasion d'exprimer votre avis général sur ces deux types de cartes.

Je pense que j'aimerais utiliser ce type de carte fréquemment

- Pour ce qui concerne la carte papier
- Pour ce qui concerne la carte interactive

1	2	3	4	5
Pas du tout d'accord				Tout à fait d'accord
1	2	3	4	5

J'ai trouvé ce type de carte inutilement complexe

- Pour ce qui concerne la carte papier
- Pour ce qui concerne la carte interactive

1	2	3	4	5
Pas du tout d'accord				Tout à fait d'accord
1	2	3	4	5

J'ai trouvé ce type de carte facile à utiliser

- Pour ce qui concerne la carte papier
- Pour ce qui concerne la carte interactive

1	2	3	4	5
Pas du tout d'accord				Tout à fait d'accord
1	2	3	4	5

Je pense que j'aurais besoin de l'aide d'une personne expérimentée pour pouvoir utiliser ce type de carte

- Pour ce qui concerne la carte papier
- Pour ce qui concerne la carte interactive

1	2	3	4	5
Pas du tout d'accord				Tout à fait d'accord
1	2	3	4	5

J'ai trouvé que les différentes fonctionnalités étaient bien conçues et intégrées dans ce type de carte

- Pour ce qui concerne la carte papier
- Pour ce qui concerne la carte interactive

1	2	3	4	5
Pas du tout d'accord				Tout à fait d'accord
1	2	3	4	5

J'ai trouvé que ce type de carte présentait un nombre important d'incohérences

- Pour ce qui concerne la carte papier
- Pour ce qui concerne la carte interactive

1	2	3	4	5
Pas du tout d'accord				Tout à fait d'accord
1	2	3	4	5

Je pense que la plupart des personnes déficientes visuelles pourraient facilement ou rapidement apprendre à utiliser ce type de carte

- Pour ce qui concerne la carte papier
- Pour ce qui concerne la carte interactive

1	2	3	4	5
Pas du tout d'accord				Tout à fait d'accord
1	2	3	4	5

J'ai trouvé que ce type de carte était peu commode lors de son utilisation

- Pour ce qui concerne la carte papier
- Pour ce qui concerne la carte interactive

1	2	3	4	5
Pas du tout d'accord				Tout à fait d'accord
1	2	3	4	5

Je me suis senti(e) en toute confiance lors de l'utilisation de ce type de carte

- Pour ce qui concerne la carte papier
- Pour ce qui concerne la carte interactive

1	2	3	4	5
Pas du tout d'accord				Tout à fait d'accord
1	2	3	4	5

J'ai eu besoin d'un long temps d'adaptation pour me sentir à l'aise avec ce type de carte

- Pour ce qui concerne la carte papier
- Pour ce qui concerne la carte interactive

1	2	3	4	5
Pas du tout d'accord				Tout à fait d'accord
1	2	3	4	5

VII.8.5 Spatial tests

L- Knowledge of landmarks [max score = 12 pts]

- **L-POI- Memory for names of points of interest:** participants need to recall the names of the landmarks that were present on the map. [max score = 6 pts; 6 items have to be recalled -> 1 pt per correct recall]

- **L-S-Memory for names of streets:** participants need to recall the names of the streets that were present on the map. [max score = 6 pts; 6 items have to be recalled -> 1 pt per correct recall]

R- Route knowledge [max score = 12 pts]

- **R-RDE-Route distance estimation:** two different routes (A-B, and A-C) are described and participants need to decide which route is the longest one. [max score = 4 pts; 4 items -> 1 pt per correct answer]

- **R-R-Route recognition:** a route is described and participants need to decide whether the route is correct or not. [max score = 4 pts; 4 items -> 1 pt per correct answer]

- **R-W-Wayfinding (route production)**: a starting point and a goal are provided, and participants need to decide which route to take. [max score = 4 pts; 4 items -> 1 pt per correct answer]

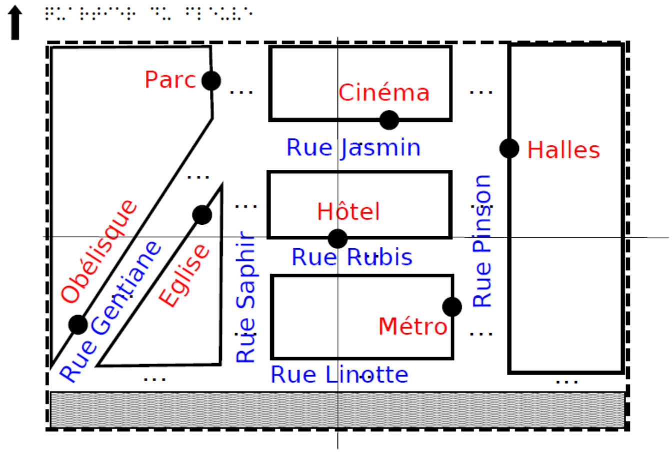
S- Survey knowledge [max score = 12 pts]

- **S-Dir-Direction estimation**: a starting point and a goal are given and participants need to indicate the direction to the goal using a clock system (e.g., at 10'clock, at 3'clock). [max score = 4 pts; 4 items -> 1 pt per correct answer]

- **S-Loc-Location estimation:** the map is cut into 4 equivalent pieces (North-East, North-West, South-East, South-West), and participants need to decide in which part of the map a series of elements are located. [max score = 4 pts; 4 items -> 1 pt per correct answer]

- **S-Dist-Survey distance estimation:** two different distances (A-B, and A-C) are described and participants need to decide which distance is the longest one as if they were a bird. [max score = 4 pts; 4 items -> 1 pt per correct answer]

VII.8.5.1 Map 1



1) L-POI : « Sans compter l'hôtel, quels étaient les noms des 6 points d'intérêt sur la carte ? »

Parc ; Cinéma ; Halles ; Métro ; Eglise ; Obélisque (souligner les réponses correctes)

Avez-vous confiance dans vos réponses ?

1	2	3	4	5

Pas du tout Tout à fait

2) L-S : « Quels étaient les noms des 6 rues sur la carte ? »

Jasmins ; Rubis ; Linottes ; Pinsons ; Saphirs ; Gentianes (souligner les réponses correctes)

Avez-vous confiance dans vos réponses ?

1	2	3	4	5

Pas du tout Tout à fait

3) R-RDE-1 :« Par la route, et en empruntant le plus court chemin, lequel de ces deux trajets est le plus long ? Trajet 1 : de l'Hôtel au Métro. Trajet 2 : de l'Hôtel au Parc. »

Trajet 2 Hôtel-Parc est le plus long Réponse :

4) R-RDE-2 : « Par la route, et en empruntant le plus court chemin, lequel de ces deux trajets est le plus long ? Trajet 1 : de l'Obélisque au Cinéma. Trajet 2 : de l'Obélisque au Parc. »

Trajet 1 Obélisque-Cinéma est le plus long Réponse :

5) R-RDE-3 :« Par la route, et en empruntant le plus court chemin, lequel de ces deux trajets est le plus long ? Trajet 1 : de l'Eglise au Halles. Trajet 2 : de l'Eglise à l'Hôtel. »

Trajet 1 Eglise-Halles est le plus long Réponse :

6) R-RDE-4 :« Par la route, et en empruntant le plus court chemin, lequel de ces deux trajets est le plus long ? Trajet 1 : du Métro à l'Obélisque. Trajet 2 : du Métro au Parc»

Trajet 2 Métro-Parc est le plus long Réponse :

Avez-vous confiance dans vos réponses ?

1	2	3	4	5

Pas du tout Tout à fait

7) R-R-1: « Ce trajet est-il correct ? Pour aller (par le chemin le plus court) du Cinéma au Métro, j'emprunte successivement la rue des Jasmins et la rue des Pinsons ». Correct

Réponse : □ Correct □ Incorrect

8) R-R-2-« Ce trajet est-il correct ? Pour aller (par le chemin le plus court) du Parc à l'Obélisque, j'emprunte successivement la rue des Saphirs et la rue des Jasmins ». Incorrect

Réponse : □ Correct □ Incorrect

9) R-R-3-« Ce trajet est-il correct ? Pour aller (par le chemin le plus court) de l'Eglise à l'Hôtel, j'emprunte successivement la rue des Gentiannes, la rue des Jasmins, et la rue des Rubis». Incorrect

Réponse : □ Correct □ Incorrect

10) R-R-4--« Ce trajet est-il correct ? Pour aller (par le chemin le plus court) des Halles au Parc, j'emprunte successivement la rue des Pinsons, la rue des Jasmins et la rue des Saphirs». Correct

Réponse : □ Correct □ Incorrect

Avez-vous confiance dans vos réponses ?

1	2	3	4	5

Pas du tout Tout à fait

11) R-W-1 : “Quelles rues dois-je successivement emprunter pour aller de l’hôtel au Parc par le chemin le plus court ? »

Rubis + Saphirs Réponse :

12) R-W-2 : “Quelles rues dois-je successivement emprunter pour aller du Métro au Cinéma par le chemin le plus court ? »

Pinsons + Jasmins Réponse :

13) R-W-3 : “Quelles rues dois-je successivement emprunter pour aller du Parc aux Halles par le chemin le plus court ? »

Saphirs + Jasmins + Pinsons Réponse :

14) R-W-4 : “Quelles rues dois-je successivement emprunter pour aller de l’Obélisque au Métro par le chemin le plus court ? »

Gentianes + Linottes + Pinsons Réponse :

Avez-vous confiance dans vos réponses ?

1	2	3	4	5

Pas du tout Tout à fait

15) S-Dir-1 : « Imaginez-vous à l’Hôtel, dans quelle direction se trouve le Cinéma par rapport à l’Hôtel? Pour répondre, utilisez le système de l’horloge pour indiquer la direction à partir de votre position (à midi, à 6h, à 3h, à 9h, à 10h, etc.) »

Cinéma à 1h par rapport à l’Hôtel Réponse :

16) S-Dir-2-« Imaginez-vous à l’Hôtel, dans quelle direction se trouve le Parc par rapport à l’Hôtel? Pour répondre, utilisez le système de l’horloge pour indiquer la direction à partir de votre position (à midi, à 6h, à 3h, à 9h, à 10h, etc.) »

Parc à entre 10h et 11h par rapport à l’Hôtel Réponse

17) S-Dir-3-« Imaginez-vous à l’Eglise, dans quelle direction se trouve l’Obélisque par rapport à l’Eglise? Pour répondre, utilisez le système de l’horloge pour indiquer la direction à partir de votre position (à midi, à 6h, à 3h, à 9h, à 10h, etc.) »

Obélisque entre 7h et 8h par rapport à l’Eglise Réponse :

18) S-Dir-4-« Imaginez-vous à l'Eglise, dans quelle direction se trouve les Halles par rapport à l'Eglise? Pour répondre, utilisez le système de l'horloge pour indiquer la direction à partir de votre position (à midi, à 6h, à 3h, à 9h, à 10h, etc.) »

Halles à 2h par rapport à l'Eglise Réponse :

Avez-vous confiance dans vos réponses ?

1	2	3	4	5

Pas du tout Tout à fait

Si besoin décrire la grille (tracer une ligne verticale, une ligne horizontale à partir de l'hôtel)

19) S-Loc-1 : « Imaginez que la carte est coupée en 4 parties équivalentes à partir du point central qu'est l'Hôtel (partie nord-est, nord-ouest, sud-est et sud-ouest). Dans quelle partie de la carte se trouvent les Halles ? »

Halles dans la partie Nord-Est Réponse :

20) S-Loc-2 : « Imaginez que la carte est coupée en 4 parties équivalentes à partir du point central qu'est l'Hôtel (partie nord-est, nord-ouest, sud-est et sud-ouest). Dans quelle partie de la carte se trouve le Cinéma? »

Cinéma dans la partie Nord-Est Réponse :

21) S-Loc-3 : « Imaginez que la carte est coupée en 4 parties équivalentes à partir du point central qu'est l'Hôtel (partie nord-est, nord-ouest, sud-est et sud-ouest). Dans quelle partie de la carte se trouve l'Obélisque ? »

Obélisque dans la partie Sud-Ouest Réponse :

22) S-Loc-4 : « Imaginez que la carte est coupée en 4 parties équivalentes à partir du point central qu'est l'Hôtel (partie nord-est, nord-ouest, sud-est et sud-ouest). Dans quelle partie de la carte se trouve le Parc? »

Parc dans la partie Nord-Ouest Réponse :

Avez-vous confiance dans vos réponses ?

1	2	3	4	5

Pas du tout Tout à fait

23) S-Dist-1 : « A vol d'oiseau (c'est-à-dire sans emprunter les rues, mais en faisant comme si vous pouviez aller en ligne droite par les airs comme un oiseau), lequel de ces deux trajets est le plus long ? Hôtel-Obélisque ou Hôtel-Métro ? »

Hôtel-Obélisque plus long Réponse :

24) S-Dist-2 : « A vol d'oiseau (c'est-à-dire sans emprunter les rues, mais en faisant comme si vous pouviez aller en ligne droite par les airs comme un oiseau), lequel de ces deux trajets est le plus long ? Hôtel-Eglise ou Hôtel-Halles ? »

Hôtel-Halles plus long Réponse :

25) S-Dist-3 : « A vol d'oiseau (c'est-à-dire sans emprunter les rues, mais en faisant comme si vous pouviez aller en ligne droite par les airs comme un oiseau), lequel de ces deux trajets est le plus long ? Cinéma-Parc ou Cinéma-Halles ? »

Cinéma-Parc plus long Réponse :

26) S-Dist-4 : « A vol d'oiseau (c'est-à-dire sans emprunter les rues, mais en faisant comme si vous pouviez aller en ligne droite par les airs comme un oiseau), lequel de ces deux trajets est le plus long ? Halles-Parc ou Halles-Obélisque? »

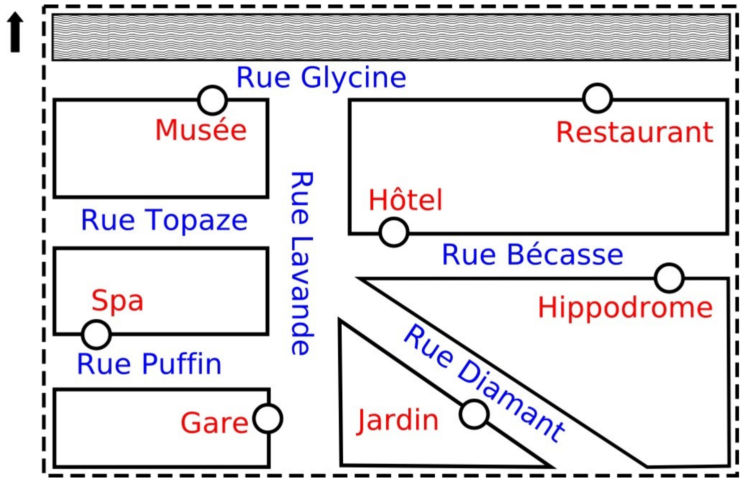
Halles-Obélisque plus long Réponse :

Avez-vous confiance dans vos réponses ?

1	2	3	4	5

Pas du tout Tout à fait

VII.8.5.2 Map 2



1) L-POI : « Sans compter l'hôtel, quels étaient les noms des 6 points d'intérêt sur la carte ? »

Musée ; Restaurant ; Spa ; Gare ; Jardin ; Hippodrome (souligner les réponses correctes)

Avez-vous confiance dans vos réponses ?

1	2	3	4	5

Pas du tout Tout à fait

2) L-S : « Quels étaient les noms des 6 rues sur la carte ? »

Glycines ; Topazes ; Puffins ; Lavandes ; Diamants ; Bécasses (souligner les réponses correctes)

Avez-vous confiance dans vos réponses ?

1	2	3	4	5

Pas du tout Tout à fait

3) R-RDE-1 :« Par la route, et en empruntant le plus court chemin, lequel de ces deux trajets est le plus long ? Trajet 1 : de l'Hôtel à la Gare. Trajet 2 : de l'Hôtel au Spa. »

Trajet 2 Hôtel-Spa est le plus long Réponse :

4) R-RDE-2 : « Par la route, et en empruntant le plus court chemin, lequel de ces deux trajets est le plus long ? Trajet 1 : de la Gare au Spa. Trajet 2 : de la Gare au Jardin. »

Trajet 1 Gare- Jardin est le plus long Réponse :

5) R-RDE-3 :« Par la route, et en empruntant le plus court chemin, lequel de ces deux trajets est le plus long ? Trajet 1 : du Musée au Jardin. Trajet 2 : du Musée à l'Hippodrome. »

Trajet 1 Musée-Hippodrome est le plus long Réponse :

6) R-RDE-4 :« Par la route, et en empruntant le plus court chemin, lequel de ces deux trajets est le plus long ? Trajet 1 : du Restaurant au Spa. Trajet 2 : du Restaurant à l'Hôtel»

Trajet 2 Restaurant-Spa est le plus long Réponse :

Avez-vous confiance dans vos réponses ?

1	2	3	4	5

Pas du tout Tout à fait

7) R-R-1: « Ce trajet est-il correct ? Pour aller (par le chemin le plus court) du Jardin à l'Hôtel, j'emprunte successivement la rue des Diamants et la rue des Topazes ». Incorrect

Réponse : □ Correct □ Incorrect

8) R-R-2-« Ce trajet est-il correct ? Pour aller (par le chemin le plus court) de la Gare au Musée, j'emprunte successivement la rue des Lavandes et la rue des Glycines ». Correct

Réponse : □ Correct □ Incorrect

9) R-R-3-« Ce trajet est-il correct ? Pour aller (par le chemin le plus court) du Restaurant à l'Hippodrome, j'emprunte successivement la rue des Glycines, la rue des Diamants et la rue des Bécasses». Incorrect

Réponse : □ Correct □ Incorrect

10) R-R-4--« Ce trajet est-il correct ? Pour aller (par le chemin le plus court) du Spa au Musée, j'emprunte successivement la rue des Puffins, la rue des Lavandes et la rue des Glycines». Correct

Réponse : □ Correct □ Incorrect

Avez-vous confiance dans vos réponses ?

1	2	3	4	5

Pas du tout Tout à fait

11) R-W-1 : "Quelles rues dois-je successivement emprunter pour aller de l'Hippodrome à la Gare par le chemin le plus court ? »

Bécasses + Lavandes Réponse :

12) R-W-2 : "Quelles rues dois-je successivement emprunter pour aller de la Gare au Restaurant par le chemin le plus court ? »

Lavandes + Glycines Réponse :

13) R-W-3 : "Quelles rues dois-je successivement emprunter pour aller du Spa à l'Hôtel par le chemin le plus court ? »

Puffins + Lavandes + Bécasses Réponse :

14) R-W-4 : "Quelles rues dois-je successivement emprunter pour aller du Jardin au Musée par le chemin le plus court ? »

Diamants + Lavandes + Glycines Réponse :

Avez-vous confiance dans vos réponses ?

1	2	3	4	5

Pas du tout Tout à fait

15) S-Dir-1 : « Imaginez-vous à l'Hôtel, dans quelle direction se trouve le Musée par rapport à l'Hôtel? Pour répondre, utilisez le système de l'horloge pour indiquer la direction à partir de votre position (à midi, à 6h, à 3h, à 9h, à 10h, etc.) »

Musée à entre 10h et 11h par rapport à l'Hôtel Réponse :

16) S-Dir-2-« Imaginez-vous à l'Hôtel, dans quelle direction se trouve la Gare par rapport à l'Hôtel? Pour répondre, utilisez le système de l'horloge pour indiquer la direction à partir de votre position (à midi, à 6h, à 3h, à 9h, à 10h, etc.) »

Gare à 7h par rapport à l'Hôtel Réponse :

17) S-Dir-3-« Imaginez-vous au Jardin, dans quelle direction se trouve l'Hippodrome par rapport au Jardin? Pour répondre, utilisez le système de l'horloge pour indiquer la direction à partir de votre position (à midi, à 6h, à 3h, à 9h, à 10h, etc.) »

Hippodrome à 2h par rapport au Jardin Réponse :

18) S-Dir-4-« Imaginez-vous au Jardin, dans quelle direction se trouve le Restaurant par rapport au Jardin? Pour répondre, utilisez le système de l'horloge pour indiquer la direction à partir de votre position (à midi, à 6h, à 3h, à 9h, à 10h, etc.) »

Restaurant à 1h par rapport au Jardin Réponse :

Avez-vous confiance dans vos réponses ?

1	2	3	4	5

Pas du tout Tout à fait

Si besoin décrire la grille (tracer une ligne verticale, une ligne horizontale à partir de l'hôtel)

19) S-Loc-1 : « Imaginez que la carte est coupée en 4 parties équivalentes à partir du point central qu'est l'Hôtel (partie nord-est, nord-ouest, sud-est et sud-ouest). Dans quelle partie de la carte se trouve le Musée ? »

Musée dans la partie Nord-Ouest Réponse :

20) S-Loc-2 : « Imaginez que la carte est coupée en 4 parties équivalentes à partir du point central qu'est l'Hôtel (partie nord-est, nord-ouest, sud-est et sud-ouest). Dans quelle partie de la carte se trouve le Spa? »

Spa dans la partie Sud-Ouest Réponse :

21) S-Loc-3 : « Imaginez que la carte est coupée en 4 parties équivalentes à partir du point central qu'est l'Hôtel (partie nord-est, nord-ouest, sud-est et sud-ouest). Dans quelle partie de la carte se trouve le Restaurant ? »

Restaurant dans la partie Nord-Est Réponse :

22) S-Loc-4 : « Imaginez que la carte est coupée en 4 parties équivalentes à partir du point central qu'est l'Hôtel (partie nord-est, nord-ouest, sud-est et sud-ouest). Dans quelle partie de la carte se trouve la Gare? »

Gare dans la partie Sud-Ouest Réponse :

Avez-vous confiance dans vos réponses ?

1	2	3	4	5

Pas du tout Tout à fait

23) S-Dist-1 : « A vol d'oiseau (c'est-à-dire sans emprunter les rues, mais en faisant comme si vous pouviez aller en ligne droite par les airs comme un oiseau), lequel de ces deux trajets est le plus long ? Hôtel-Jardin ou Hôtel-Musée ? »

Hôtel-Musée plus long Réponse :

24) S-Dist-2 : « A vol d'oiseau (c'est-à-dire sans emprunter les rues, mais en faisant comme si vous pouviez aller en ligne droite par les airs comme un oiseau), lequel de ces deux trajets est le plus long ? Hôtel-Spa ou Hôtel-Restaurant ? »

Hôtel-Spa plus long Réponse :

25) S-Dist-3 : « A vol d'oiseau (c'est-à-dire sans emprunter les rues, mais en faisant comme si vous pouviez aller en ligne droite par les airs comme un oiseau), lequel de ces deux trajets est le plus long ? Hippodrome-Jardin ou Hippodrome-Gare ? »

Hippodrome-Gare plus long Réponse :

26) S-Dist-4 : « A vol d'oiseau (c'est-à-dire sans emprunter les rues, mais en faisant comme si vous pouviez aller en ligne droite par les airs comme un oiseau), lequel de ces deux trajets est le plus long ? Restaurant-Musée ou Restaurant-Hippodrome? »

Restaurant-Musée plus long Réponse :

Avez-vous confiance dans vos réponses ?

1	2	3	4	5

Pas du tout   Tout
à   fait

VII.9 Advanced Non-Visual Interaction (Chapter V)

VII.9.1 SUS Questionnaire for Wizard of Oz

1) Je pense que j'aimerais utiliser cette technique de guidage fréquemment.

1	2	3	4	5

Pas du tout Tout à fait

2) J'ai trouvé cette technique de guidage inutilement complexe.

1	2	3	4	5

Pas du tout Tout à fait

3) J'ai trouvé cette technique facile à utiliser.

1	2	3	4	5

Pas du tout Tout à fait

4) Lorsque je me perds, la technique ne me permet pas de retrouver rapidement mon chemin sans l'aide de l'examinateur.

1	2	3	4	5

Pas du tout Tout à fait

5) J'ai trouvé que les différentes fonctionnalités étaient bien conçues dans cette technique.

1	2	3	4	5

Pas du tout Tout à fait

6) J'ai trouvé que cette technique présentait un nombre important d'incohérences.

1	2	3	4	5

Pas du tout Tout à fait

7) Je pense que la plupart des personnes pourraient facilement ou rapidement apprendre à utiliser ce type de technique de guidage.

1	2	3	4	5

Pas du tout Tout à fait

8) J'ai trouvé que cette technique de guidage était peu commode lors de son utilisation.

1	2	3	4	5

Pas du tout Tout à fait

9) Je pense être plus confiant grâce au guidage.

1	2	3	4	5

Pas du tout Tout à fait

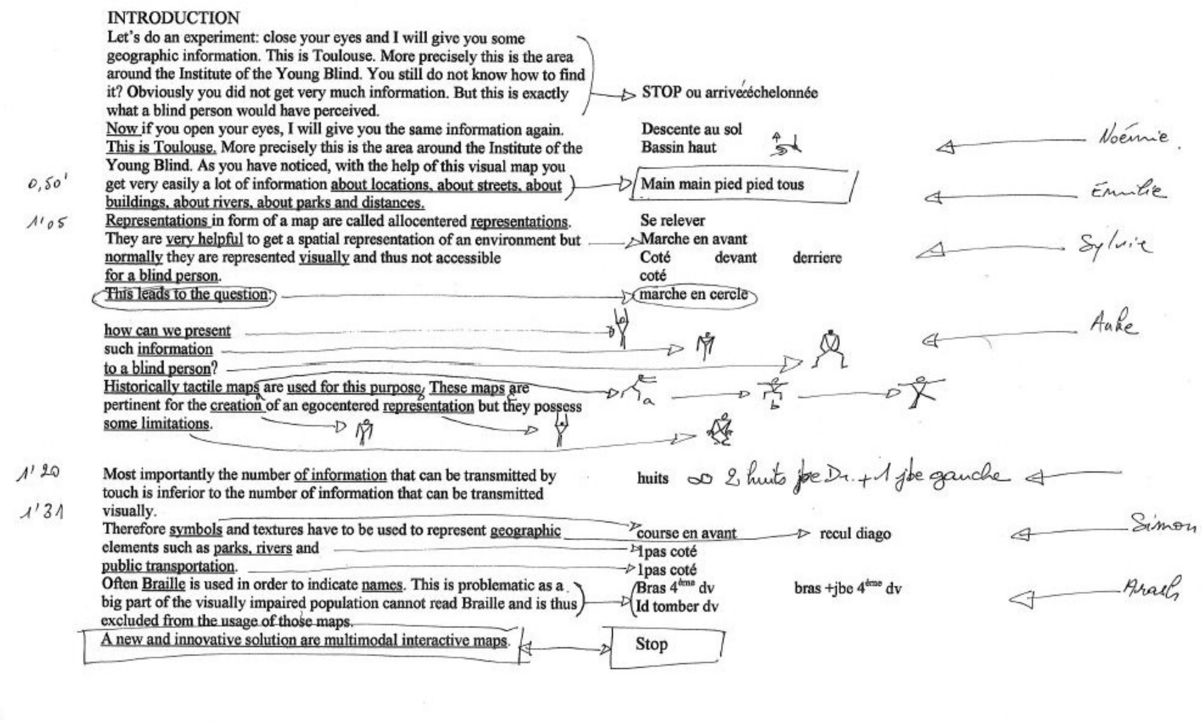
10) J'ai eu besoin d'un long temps d'adaptation pour me sentir à l'aise avec ce type de guidage.

1	2	3	4	5

Pas du tout Tout à fait

VII.10 Dance Your PhD

In December 2012 my dancing chorus presented a performance on interactive maps for visually impaired people. The choreography was accompanied by the video presented on my website (http://bit.ly/VideoIM).


INTRODUCTION

Let's do an experiment: close your eyes and I will give you some geographic information. This is Toulouse. More precisely this is the area around the Institute of the Young Blind. You still do not know how to find it? Obviously you did not get very much information. But this is exactly what a blind person would have perceived. — STOP ou arrivée échelonnée

Now if you open your eyes, I will give you the same information again. This is Toulouse. More precisely this is the area around the Institute of the Young Blind. As you have noticed, with the help of this visual map you get very easily a lot of information about locations, about streets, about buildings, about rivers, about parks and distances. — Descente au sol, Bassin haut, Main main pied pied tous — Noémie, Emilie

0,50'

1'05 Representations in form of a map are called allocentered representations. They are very helpful to get a spatial representation of an environment but normally they are represented visually and thus not accessible for a blind person. — Se relever, Marche en avant, Coté devant derriere coté — Sylvie

This leads to the question: — marche en cercle

how can we present such information to a blind person? — Aake

Historically tactile maps are used for this purpose. These maps are pertinent for the creation of an egocentered representation but they possess some limitations.

1'20 Most importantly the number of information that can be transmitted by touch is inferior to the number of information that can be transmitted visually. — huits ∞ 2 huits jbe Dr. + 1 jbe gauche

1'31 Therefore symbols and textures have to be used to represent geographic elements such as parks, rivers and public transportation. — course en avant → recul diago, 1pas coté, 1pas coté — Simon

Often Braille is used in order to indicate names. This is problematic as a big part of the visually impaired population cannot read Braille and is thus excluded from the usage of those maps. — Bras 4ème dv, Id tomber dv, bras +jbe 4ème dv — Anaël

A new and innovative solution are multimodal interactive maps. — Stop

Figure VII.6: Preparation of the choreography

Figure VII.7 The dance performance

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Tables

Anke M. BROCK

Interactive Maps for Visually Impaired People: Design, Usability and Spatial Cognition

Thesis Supervisors:

Delphine Picard - Professor, Aix Marseille University, Institut Universitaire de France

Christophe Jouffrais – CNRS Researcher, IRIT, CNRS & University of Toulouse 3, France

PhD Defense November 27th, 2013 at IRIT, University Toulouse 3 Paul Sabatier, France

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Abstract:

Knowing the geography of an urban environment is crucial for visually impaired people. Tactile relief maps are generally used, but they retain significant limitations (limited amount of information, use of braille legend, etc.). Recent technological progress allows the development of innovative solutions which overcome these limitations. In this thesis, we present the design of an accessible interactive map through a participatory design process. This map is composed by a multi-touch screen with tactile map overlay and speech output. It provides auditory information when tapping on map elements. We have demonstrated in an experiment that our prototype was more effective and satisfactory for visually impaired users than a simple raised-line map. We also explored and tested different types of advanced non-visual interaction for exploring the map. This thesis demonstrates the importance of interactive tactile maps for visually impaired people and their spatial cognition.

Keywords:

Human computer interaction; interactive maps; accessibility; visual impairment; non-visual interaction; multi-touch; participatory design; usability; spatial cognition

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Discipline: Computer Science

Institut de Recherche en Informatique de Toulouse — UMR 5505

Université Paul Sabatier, 118 route de Narbonne, 31 062 Toulouse Cedex 4, France

Anke M. BROCK

Cartes Interactives pour Déficients Visuels: Conception, Utilisabilité et Cognition Spatiale

Directeurs de thèse:

Delphine Picard - Professor, Aix Marseille University, Institut Universitaire de France
Christophe Jouffrais – Chargé de Recherche CNRS, IRIT, CNRS & University of Toulouse 3

Soutenu le 27 Novembre 2013 à l'IRIT, Université Toulouse 3 Paul Sabatier, France

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Résumé:

Connaître la géographie de son environnement urbain est un enjeu important pour les personnes déficientes visuelles. Des cartes tactiles en relief sont généralement utilisées mais elles présentent des limitations importantes (nombre limité d'informations, recours à une légende braille). Les nouvelles technologies permettent d'envisager des solutions innovantes. Nous avons conçu et développé une carte interactive accessible, en suivant un processus de conception participative. Cette carte est basée sur un dispositif multi-touch, une carte tactile en relief et une sortie sonore. Ce dispositif permet au sujet de recueillir des informations en double-cliquant sur certains objets de la carte. Nous avons démontré expérimentalement que ce prototype était plus efficace et plus satisfaisant pour des utilisateurs déficients visuels qu'une carte tactile simple. Nous avons également exploré et testé différents types d'interactions avancées accessibles pour explorer la carte. Cette thèse démontre l'importance des cartes tactiles interactives pour les déficients visuels et leur cognition spatiale.

Keywords:

Interaction homme-machine ; cartes interactives ; accessibilité ; déficience visuelle ; interaction non-visuelle; multi-touch ; conception participative; cognition spatiale

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Discipline: Informatique

Institut de Recherche en Informatique de Toulouse — UMR 5505

Université Paul Sabatier, 118 route de Narbonne, 31 062 Toulouse Cedex 4, France